Light Thermal DM & The Higgs Portal

Gordan Krnjaic

Fermilab

1512.04119

Dark Sectors Workshop SLAC, April 30, 2016
Vector Portal: Many Options
(Philip’s Plenary Talk)

Scalar

Fermion

Thermal Elastic

Thermal Inelastic

Scalar Thermal Relic DM

$y = \epsilon_0 \alpha (m_\phi m_A')^4$

$\chi (\text{MeV})$

$10^{-16}$

Scalar Inelastic DM

$y = \epsilon_0 \alpha (m_\phi m_A')^4$

$\chi (\text{MeV})$

$10^{-16}$

Dirac Fermion Thermal Relic DM

$y = \epsilon_0 \alpha (m_\phi m_A')^4$

$\chi (\text{MeV})$

$10^{-16}$

Pseudo–Dirac Thermal Relic DM

$y = \epsilon_0 \alpha (m_\phi m_A')^4$

$\chi (\text{MeV})$

$10^{-16}$
Historical Analogy
Understanding the Weak Force

Discovery of radioactivity (1890s)

**Fermi Scale identified** \( G_F \sim \frac{1}{(100 \ \text{GeV})^2} \) (1930s)

Non-Abelian Gauge Theory (1950s)

Higgs Mechanism (1960s)

W/Z bosons (1970s)

Higgs discovered (2010s)

Each step required revolutionary theoretical/experimental leaps

\[ t \sim 100 \ \text{years} \]
How long will we wait for DM?

Discovery of missing mass (1930s)

Rotation curves (1970s)

CMB power spectrum (1990s)

Relevant scale? > 2016

Non-gravitational interactions not guaranteed
No clear target of opportunity

Discovery time frame? $t > 80$ yrs
What’s so great about “Thermal”?  
Advantage #1: Minimum Annihilation Rate

Equilibrium, achieved easily with a tiny DM/SM coupling

$$n_{DM} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$

Generically overproduces DM
Requires *much larger* annihilation cross section to deplete

$$\sigma v \geq \sigma v_{\text{relic}} \sim 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$$

\[\Rightarrow\] symmetric thermal DM

Saturday, April 30, 16
What's so great about "Thermal"?
Advantage #2: Narrow(er) Mass Range

< 10 keV DM too hot
spoils structure formation

LDM region is conceptually different

> 100 TeV DM
overproduced
Heavy vs. Light # 1
LDM needs new forces

Heavy DM can avoid overproduction w/ SM gauge bosons

\[ \sigma v \sim \frac{\alpha_W^2 m_W^2}{m_Z^4} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \]

for \( m_\chi \sim \text{ TeV} \)

For LDM, annihilation via SM forces is too weak

\[ m_\chi \sim \text{ MeV} \implies \sigma v \ll 3 \times 10^{-26} \text{ cm}^3/\text{s} \]

LDM overproduced unless there are light, new “mediators”
Avoiding LDM Overproduction
Choose light mediator

Must be SM singlet, options limited by SM gauge invariance

**Vector Portal**
mix w/ photon

\[ \epsilon F_{\mu \nu} F'_{\mu \nu} \]

**Neutrino Portal**
mix w/ RHN

\[ H^\dagger LN \]

**Higgs Portal**
mix w/ SM Higgs

\[ (H^\dagger H) \phi \]
Avoiding LDM Overproduction
Choose light mediator

Must be SM singlet, options limited by SM gauge invariance

**Vector Portal**
mix w/ photon

**:math: X :**

Lots of attention here

**Neutrino Portal**
mix w/ RHN

**:math: X :**

See Alex Friedland’s Talk

**Higgs Portal**
mix w/ SM Higgs

**:math: (H^+ H) \phi :**

\( \sin \theta \)

SM coupling \( \propto \) fermion mass \( \phi \)

\( h \)
Heavy vs. Light # 2
CMB rules out LDM < 10 GeV?

Cross section is smaller @ CMB \( \sigma v \propto v^2 \)
Annihilation shuts off @ CMB e.g. \( n_\chi \neq n_{\bar{\chi}} \)
How to survive CMB for scalar mediator?
Choose LDM candidate & coupling

Scalar DM
both s-wave!

Need particle asymmetry or inelasticity for CMB safety
How to survive CMB for scalar mediator?
Choose LDM candidate & coupling

Scalar DM
both s-wave!

Need particle asymmetry or inelasticity for CMB safety

Fermion DM
\( g_\chi \phi \bar{\chi} \chi \)

Can also include \( \phi \bar{\chi} \gamma^5 \chi \)
must be tiny (adds s-wave piece)

Both CMB ok!
\( \sigma v \propto v^2 \)
Thermal Target: Direct Annihilation to SM

\[ gf = g_e \left( \frac{m_f}{m_e} \right) \]

Coupling scales with SM fermion mass

\[ \sigma \nu = \sum_f (\sigma \nu)_f \propto g_\chi g_e^2 \left( \frac{m_\chi}{m_\phi} \right)^4 \frac{1}{m_\chi^2} \]

In analogy with dark photon target

\[ y \equiv g_\chi^2 g_e^2 \left( \frac{m_\chi}{m_\phi} \right)^4 \]

Normalized to electron coupling because it’s relevant for every mass point
Large theory uncertainty in SM coupling near QCD scale

Estimate from different numerical extractions from light Higgs literature

\[ g_f(s) \approx \sin \theta \sqrt{\frac{8\pi}{m_h} \Gamma(h \rightarrow \text{SM})} \bigg|_{m_h = \sqrt{s}} \]
Thermal Target: Rare B/K Decays

2/3 body decays to LDM/mediator

\[ B^+ \rightarrow K^+ \phi, \ K^+ \chi \chi \]
\[ K^+ \rightarrow \pi^+ \phi, \ \pi^+ \chi \chi \]

constrained by

\[ B^+ \rightarrow K^+ \nu \bar{\nu} \quad K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

Annihilation rate set by *small* yukawas

FCNC constraints set by *top* yukawa

Bird, Jackson, Kowalewski, Pospelov
arXiv: 0401195
How to compare meson decays w/target?

On shell decays to mediator independent of DM

Need to assume DM mass/coupling for thermal comparison

\[ \Delta \text{Br}(B^+ \to K^+ \bar{E}) \propto g_f^2 = y \times \frac{1}{g_{\chi}^2} \left( \frac{m_\phi}{m_\chi} \right)^4 \]

Conservative worst-case “y” reach \( g_\chi, \ m_\phi/m_\chi \to \mathcal{O}(1) \)
Thermal Target: Other Constraints

Higgs Invisible Width
Possibly compensate with additional $h$ production, but can’t avoid interference with $4l$ final state

Low Mass Direct Detection
assuming elastic scattering
**Direct Annihilation: Ruled Out**

![Graph showing constraints on Dirac fermion DM that annihilates through a light, Higgs-mixed mediator.](chart)

In the regime where the mediator is heavier than the DM, the annihilation rate is independent of the mediator mass.

**Collider and meson constraints use conservative** $m_\phi = 3m_\chi, \quad g_\chi = 1$
DM Model Variations? (still assuming direct annihilation)

Invisibly Decaying Scalar Mediator, Dirac DM, $m_\phi > m_\chi$

Asymmetric DM? No, annihilation rate bigger

Scalar symmetric DM? No, death by CMB

Inelasticity? No, colliders/mesons don't care

Additional motivation for dark photon DM program

Collider and meson constraints use conservative

$m_\phi = 3m_\chi, \ g_\chi = 1$
Annihilation to Mediators: Thermal Target?

Annihilation rate independent of SM

\[ \sigma v (\chi \chi \rightarrow \phi \phi) = \frac{3 g^4 v^2}{128 \pi m^2\chi} \]

Mediator decays visibly to SM final states

Can still produce/observe mediator, but no direct target

So long as annihilation is p-wave
DM doesn’t matter for bounds
Next best thing?
Minimum mixing for thermal production

Assuming Higgs-mediator mixing *alone* produces thermal DM

\[ \Gamma_{\text{SM} \rightarrow \chi \bar{\chi}} = \sum_f n_f(T) \langle \sigma |v| \rangle_{f \bar{f} \rightarrow \chi \bar{\chi}} \]

Requiring DM production > Hubble at *some point* in early universe

\[ \sin^2 \theta \gtrsim \frac{53\pi^3 \sqrt{g_*(m_t)} m_t}{g_\chi \zeta(3) m_{Pl}} \approx 2 \times 10^{-13} \]

Reaching this sensitivity for \( g_\chi \sim \mathcal{O}(1) \) would rule out thermal DM for the visibly decaying scenario
Mediator mixing bounds (comparable DM mass)

Beam dump and meson bounds
Clarke, Foot, Volkas 1310.8042

Thermal DM can live anywhere unshaded
Mediator mixing bounds (hierarchical DM mass)

Visibly Decaying Scalar Mediator \( m_\phi < m_\chi \)

For Direct Detection \( m_\chi = 10m_\phi \), \( g_\chi = \) Thermal

DM Never Thermalizes Through Mixing

Larger hierarchy no longer LDM < GeV
Conclusions

Higgs portal thermal target already covered for minimal case
Direct annihilation scenario ruled out by rare meson and Higgs bounds
   Insensitive to DM model variations

“Secluded” annihilation to mediators still viable
   Much of remaining territory (but not all!) to be covered with
   next generation DD and beam dump searches (SHiP)

SHiP and other dark photon searches may be comparable
   Where else should we be looking for remaining real estate?

Options at low mass are limited, leave no stone unturned