Dynamical Dark Matter at the Lifetime Frontier

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Based on work done in collaboration with:


Section in MATHUSLA white paper
Dynamical Dark Matter

- Observational constraints impose a stringent bound \( \gtrsim 10^{28} \text{ s} \) on the lifetimes of traditional dark-matter candidates \( \chi \) which decay to visible-sector states over a large mass range \( \mathcal{O}(100 \text{ keV}) \lesssim m_\chi \lesssim \mathcal{O}(\text{EeV}) \).

- Such “hyperstability” is therefore a requirement in traditional dark-matter scenarios.

- **Dynamical Dark Matter** (DDM) is an alternative framework for dark-matter physics which provides a novel way of evading this hyperstability requirement, thereby enlarging the theory space of viable dark-matter scenarios. [Dienes, BT, '11]

In DDM scenarios...

- The dark-matter candidate is an ensemble consisting of a potentially vast number of constituent particle species.

- The individual abundances of the constituents are balanced against decay rates across the ensemble such that constraints are satisfied.

- The DM abundance and equation of state also exhibit a non-trivial time-dependence beyond that associated with Hubble expansion.
A Snapshot of the Cosmic Pie: Past, Present, and Future

Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

Dark Energy 68.3%

Atoms 4.9%

Will decay in the future

Decayed in the past

RIGHT NOW

Time
Concrete realizations of the DDM framework often also give rise to **distinctive signatures** at colliders, direct-detection experiments, or indirect-detection experiments. These include...

- Marked differences in kinematics of visible particles at colliders. [Dienes, Su, BT '12]

- Distinctive energy distributions for nuclear recoils at direct-detection experiments. [Dienes, Kumar, BT '12]

- Cosmic-ray fluxes consistent with data at low energies, but which exhibit strange behavior at high energies [Dienes, Kumar, BT '13]

- Characteristic correlations between spectral features at future gamma-ray telescopes [Boddy, Dienes, Kim, Kumar Park, BT '16]
A DDM ensemble is not simply an arbitrary collection of dark states.

Its structure is determined by an organizing principle which specifies the properties of those states in terms of only a few underlying parameters.

This organizing principle gives rise to a set of scaling relations which describe how the masses, abundances, decay widths, etc., of the DM particles scale in relation to one another across the ensemble:

The structure of the ensemble specified by these scaling relations often includes not only cosmologically stable states which contribute to $\Omega_{DM}$ today, but states with far shorter lifetimes as well.

Measuring the properties of these less stable states therefore translates into concrete predictions about the dark matter.
DDM at the Lifetime Frontier

- Realizations of the DDM framework often include not only cosmologically stable states, which contribute to $\Omega_{DM}$ today, but also states with far shorter lifetimes.

- Detectors such as MATHUSLA, which augment the detection capabilities of the main LHC detectors, could probe the structure of a DDM ensemble by its less stable constituents.

MAssive TIming Hodoscope for Uitra STable neutraL pArticles

[J. P. Chou, D. Curtin, H. Lubatti ‘16]
Advantages of MATHUSLA

- Design proposal involves a $(200 \text{ m}) \times (200 \text{ m}) \times (20 \text{ m})$ decay volume.

- Similar geometric acceptance for LLP decays as the main LHC detectors.

- However, MATHUSLA does not have that same complicated triggering requirements or background issues as the main detectors.

- Excellent background rejection: near-perfect signal efficiency.
  
  [J. P. Chou, D. Curtin, H. Lubatti ‘16]

- A mere $\sim 4$ LLP events at the HL-LHC would be sufficient for discovery.
The Scaling Relations

- How DDM manifests itself at MATHUSLA involves an interplay between the scaling relations which govern the ensemble.

- Example model: ensemble of DM particles $\chi_n$ with masses $m_n$, where $n = 0, 1, 2, ..., N$.

**Mass Spectrum**

$$m_n = m_0 + n^\delta \Delta m$$

**Abundances**

$$\Omega_n = \Omega_0 \left( \frac{m_n}{m_0} \right)^\gamma$$

(not really relevant here)

**Decay Widths**

$$\Gamma_n = \Gamma_0 \left( \frac{m_n}{m_0} \right)^\gamma$$

**Couplings to $\phi$**

$$c_{mn} = c_0 \delta_{mn} \left( \frac{m_n}{m_0} \right)^\xi$$
Important Questions

• How many ensemble constituents contribute significantly to the MATHUSLA signal?
  
  Define $n_{\text{min}}$ and $n_{\text{max}}$ to delimit the range of states that contribute 90% of the overall signal rate.

• How many constituents are cosmologically stable?
  
  Let $n_{\text{CS}}$ be the $n$ value of the shortest-lived cosmologically-stable $\chi_n$.

• Are there constituents which would characteristically decay within the main detector? (If there are, we would presumably have seen them.)
  
  Determine lowest $n$ for which $\beta\gamma c \tau_{\text{min}} < 1 \text{ m}$. Should be greater than $N$. 

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**Cosmologically Stable** (Can contribute to $\Omega_{\text{DM}}$ today)

0 1 2 ... $n_{\text{CS}}$ $n_{\text{min}}$ $n_{\text{max}}$ ...

**Contribute 90% of the overall signal**

**States with $\beta\gamma c \tau_{\text{min}} < 1 \text{ m}$** (hopefully none exist)

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**masses**

**lifetimes**
Detection Prospects: Sanity Check

- Consider an example model in which $\phi$ couples directly to quark-antiquark pairs and can be produced at threshold via quark fusion.

- Choose coupling $c_0$ such that the total branching fraction for all decays of the form $\phi \to \chi_m \chi_n$ is $\text{BR}_{\chi\chi} = 0.5$.

- For $m_\phi \approx 2$ TeV, we find that $\sigma_\phi \times \text{BR}_{\chi\chi} \sim 100$ fb. This is (just) sufficient for a discovery at MATHUSLA.

  Significantly larger $m_\phi$  \hspace{1cm} $\sigma_\phi \times \text{BR}_{\chi\chi} \ll 100$ fb  \hspace{1cm} (signal unobservable)

  Significantly smaller $m_\phi$  \hspace{1cm} Ruled out by ATLAS/CMS searches in monojet + MET, dijet channels

Demonstrates that MATHUSLA is indeed capable of probing realistic DDM scenarios.

- Moreover, for this reason, we take $m_\phi = 2$ TeV, as our benchmark value in what follows.
The Reach of MATHUSLA within DDM Parameter Space

- Contours show minimum value of $\sigma_{\phi} \times \text{BR}_{\chi\chi}$ within parameter space required in order to observe $\sim 4$ LLP events are during the HL-LHC run.
The Reach of MATHUSLA within DDM Parameter Space

- Contours show minimum value of $\sigma_\phi^{\min} \times BR_{\chi\chi}$ within parameter space required in order to observe $\sim 4$ LLP events during the HL-LHC run.

**Most auspicious regions for DDM Discovery**

$\sigma_\phi^{\min} \times BR_{\chi\chi} \lesssim 10^3 \text{ fb}$

$n_{CS} \gg 1$

- $m_0 = 100 \text{ keV}$, $m_0/\Delta m = 0.1$, $\delta = 1.5$
- $m_0 = 100 \text{ keV}$, $\xi = 0$, $\delta = 1.5$
Summary

- DDM ensembles often include not only cosmologically-stable states that serve as dark matter today, but also far less stable states that manifest as LLPs.

- These LLPs can lead to signals at dedicated detectors like MATHUSLA.

- We have explored the reach of MATHUSLA within the parameter space of DDM scenarios and identified particularly auspicious regions within that parameter space within which a significant number of cosmologically-stable $\chi_n$ contribute to $\Omega_{DM}$ today, while a discovery is possible at MATHUSLA due to the less stable $\chi_n$.

- The properties of all ensemble constituents are determined by the same set of scaling relations. Thus, measuring the properties of the LLPs allows us to make concrete predictions about the properties of the dark matter.

- In principle, correlations between signals at MATHUSLA and signals at the main LHC detector can yield even more information about the structure of the ensemble.