

Exploring exponential dark matter production mechanisms

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Some results in Dark matter

- Most talks in DM start with the null results!
- Now there is some result

We report on a search for dark matter particles interacting with xenon nuclei in an exposure of 2.84 tonne-years with the LUX-ZEPLIN (LZ) experiment. An extended nuclear recoil energy window up to approximately 270 keV enables searches for effective field theory and inelastic models of dark matter where high-energy recoils account for a larger fraction of the predicted recoil spectrum compared to the nominal spin independent interaction. We observe one event with characteristics consistent with a nuclear recoil of 248 ± 23 (stat) ± 23 (sys) keV, in a region where the known background expectation is low. A profile likelihood ratio test finds tension with the background-only hypothesis at a global significance of 2.6σ when accounting for look-elsewhere effects, with a maximum local significance of 3.4σ across the models tested. We describe the analysis and event of interest, the background model used in the statistical inference, and detail several of the rare background topologies considered.

Figure: [arXiv:2609.02823 [hep-ex]].

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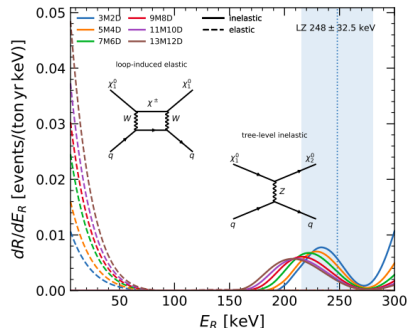


FIG. 1. Recoil spectra for our benchmark models. For each multiplet, the solid line is the tree-level inelastic contribution, while the dashed line is the loop-induced elastic contribution. The LZ observation is shown by the blue band.

Figure: [arXiv:2609.04144 [hep-ph]].

Broad questions in the field of dark matter

- Q1. How was dark matter produced in the early universe?
- Q2. Given a mechanism, what is its allowed mass range?
- Q3. Can we probe it's particle nature at experiments?

Other important questions follow ...

Q1: How is dark matter produced in the early universe

- Thermal: Either coupled to SM bath or hidden bath
- Non-thermal: axions, FIMPs, PBHs etc.
- The mass of dark matter particles cover a broad spectrum $\Rightarrow 10^{-22}$ eV to 10^{3-4} solar mass.

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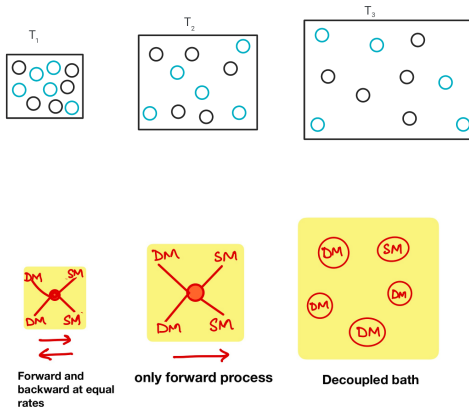
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Simplest possibility: Thermal production of dark matter

We know how standard model particles are produced in the early universe



Mass range of DM $\mathcal{O}(\text{keV})$ to $\mathcal{O}(100) \text{ TeV} \Rightarrow$ detectable at experiments!

A typical zeroth-moment Boltzmann equation for such a process is given as:

$$\frac{1}{a^3} \frac{d}{dt} (n_\chi a^3) = - \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4} \times \\ (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) |M|^2 \times \\ \left(f_\chi(p_1) f_\chi(p_2) - f_{\text{SM}}^{\text{eq}}(p_3) f_{\text{SM}}^{\text{eq}}(p_4) \right)$$

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$$f_{\chi}(p, T) = n_{\chi}(T)/n_{\chi}^{\text{eq}}(T)f_{\chi}^{\text{eq}}(p, T) .$$

i.e. dark matter traces the (*kinetic*) equilibrium distribution

- DM relic density simpler to solve

$$\frac{1}{a^3} \frac{d}{dt} (n_{\chi} a^3) = -\langle \sigma v \rangle (n_{\chi}^2 - n_{\chi}^{\text{eq}2})$$

- Thermal scenarios hence well motivated from several perspectives
- Null results → other mechanisms, better detection or non-standard cosmologies

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Scenarios with departures from thermal equilibrium

- The first classic case here is of **freeze-in** with negligible number density in the early universe.
- BE simple: since we can neglect $f_\chi \ll f_{\text{SM}}^{\text{eq}}$.
- **Hidden sector freeze-out**: In this, although dark matter is decoupled from the SM bath but it is assumed to be a part of another thermal sector with a different temperature T_χ .
- Hence again the distribution function while solving the BE can be written up in terms of the equilibrium distribution function but with a different temperature.
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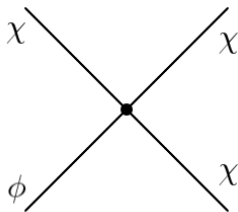
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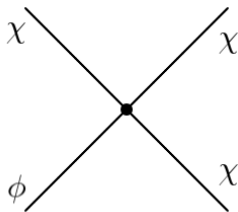
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Exponential growth mechanism (2103.16572, 2104.05684)



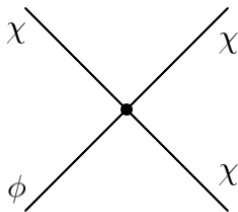
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- Exponential production continues until the process becomes Boltzmann suppressed

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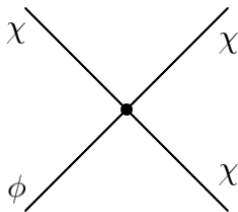
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A standard assumption while determining abundance for the thermal scenarios

- With this, the dark matter density can be estimated by considering the zeroth moment of the Boltzmann equation:

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Exponential growth mechanism continued...

Ques: Can we make the equilibrium assumption?

- Usually the assumption works well for thermal or nearly thermal scenarios.
- Production of dark matter in our case non-thermal.
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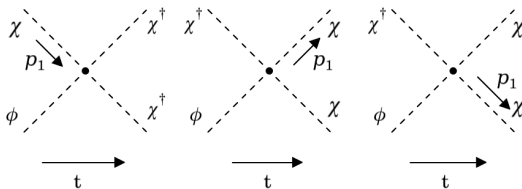
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A case study for non-thermal dark matter

The production is through interaction via thermal mediator $\mathcal{L}_{\text{int}} = \frac{1}{3}\chi^3\phi + \text{h.c.}$



First diagram: Annihilation of DM with p_1 :

Second and third diagram: Creation of DM with p_1 :

Boltzmann equation for dark matter abundance

$$\begin{aligned}\mathcal{L}[f_\chi(p_1, t)] &= \left(\frac{\partial}{\partial t} - H p_1 \frac{\partial}{\partial p_1} \right) f_\chi(p_1, t), \\ \mathcal{C}[f_\chi(p_1, t)] &= \mathcal{C}_I[f_\chi(p_1, t)] + \mathcal{C}_{II}[f_\chi(p_1, t)] \quad \text{where} \\ \mathcal{C}_I[f_\chi(p_1, t)] &= -\frac{1}{2E_1 S} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \times f_\chi(p_1, t) f_\phi^{\text{eq}}(p_2, t) \\ &\quad \times \int \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times |M|^2 \\ \mathcal{C}_{II}[f_\chi(p_1, t)] &= +2 \frac{1}{2E_1 S} \int \frac{d^3 p'_2}{(2\pi)^3 2E'_2} \frac{d^3 p'_3}{(2\pi)^3 2E'_3} \frac{d^3 p'_4}{(2\pi)^3 2E'_4} \\ &\quad \times (2\pi)^4 \delta^4(p'_3 + p'_2 - p_1 - p'_4) \times |M|^2 \times f_\chi(p'_3, t) f_\phi^{\text{eq}}(p'_2, t) .\end{aligned}$$

Integro-differential coupled equations

Boltzmann equation for dark matter abundance

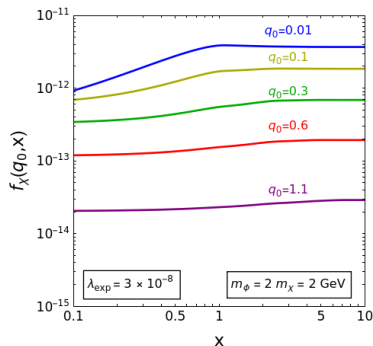
- Solve in comoving momentum frame where $q = pa$
- Discretize the comoving momenta i.e. $f(q_i, x) \equiv f_i(x)$ to solve the coupled differential equation

$$\frac{d}{dx} \begin{pmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{pmatrix} = A[x] \begin{pmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{pmatrix}$$

Need to specify initial distribution function $\rightarrow$ initial condition dependent problem

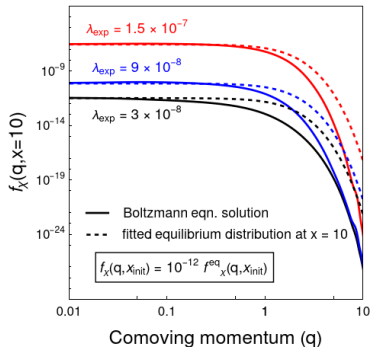
Initial condition 1: Scaled equilibrium distribution

$$f_{\chi}(q, x_{\text{init}}) = 10^{-12} f_{\chi}(q, x_{\text{init}})$$



Each momentum grows and freezes

Initial condition 1: Scaled equilibrium distribution continued...

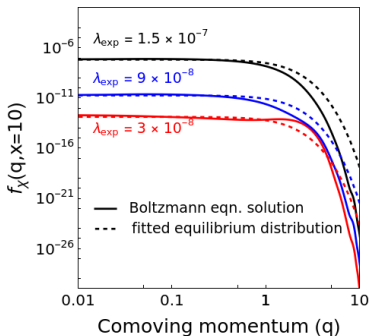
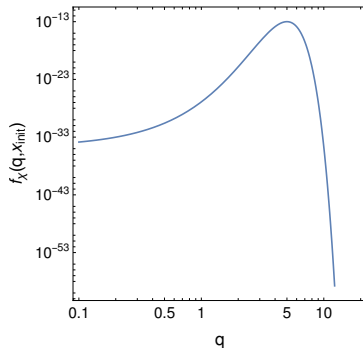


Equilibrium behavior for low momentum modes

Intital Condition 2: Out of equilibrium decays of a heavy particle

- DM could have been produced by something like inflaton decay (but the number is small)

$$f_{\chi}(q, x_{\text{init}}) = 10^{-13} \exp^{-2(q-5)^2}$$



Equilibrium behavior for low momentum modes repeat here

Initial condition independence

- In both cases we see initial condition independence.

- Why this happens?

- Mean free path: $\lambda \propto \frac{1}{\sigma} \sim \frac{q^2}{\text{coupling}^2}$
- Smaller momentum, and larger couplings $\Rightarrow$ small mean free paths
- Larger momentum and smaller couplings $\Rightarrow$ higher mean free paths come in equilibrium later.
- But the behaviour is same for any scattering process of a particle.
- We reach initial condition independence in cases where systems reach equilibrium.
- The reason we see fast equilibrium approach is because of the exponential dependence.

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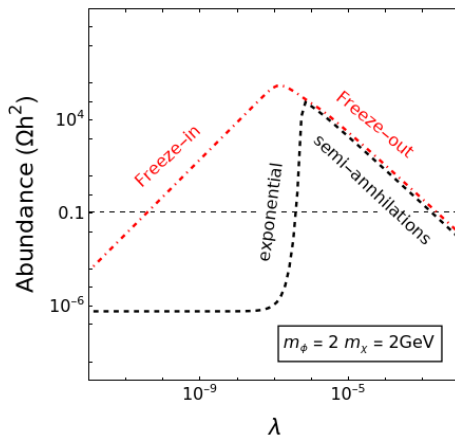
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Phase diagram assuming equilibrium assumption



Fast approaching behaviour of the exponential growth towards equilibrium.

Summary

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What kind of models can give rise to these phenomena?

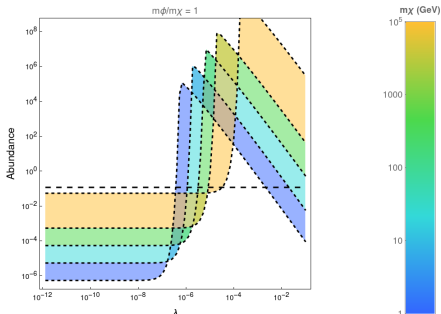
- Basically all models explaining semi-annihilations in the low coupling regions.
- A Z_3 symmetric dark matter interaction with a singlet scalar $\Rightarrow \chi^3\phi + \text{h.c.}$
- A mass-mixed fermion having self interactions via scalar/gauge boson $\Rightarrow \Delta m \overline{\chi}_1 \chi_2$ with $\overline{\chi}_1 \chi_1 \phi$ or $\overline{\chi}_1 \gamma^\mu \chi_1 Z'_\mu$

More generic features of the exponential growth models

In collaboration with Rahul Srivastava and Ranjeet Kumar

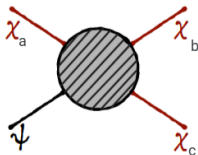
The question we are interested in asking is how high basically the mass of the dark matter can be here?

- Dominant production by scattering, therefore $\phi \rightarrow 3\chi$ (forbidden)
 $\Rightarrow m_\phi \leq 3m_\chi$
- $m_\phi > m_\chi$ or $m_\chi > m_\phi$.
- Like freeze-in, the lower mass will be determined by the bounds of free-streaming, the higher mass will depend on initial conditions, unitarity



Multi-component DM

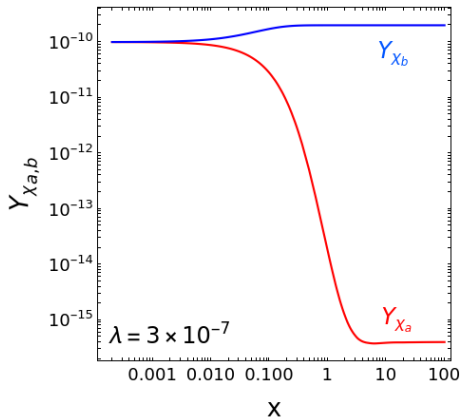
In discussion with Manibrata Sen and Soumen



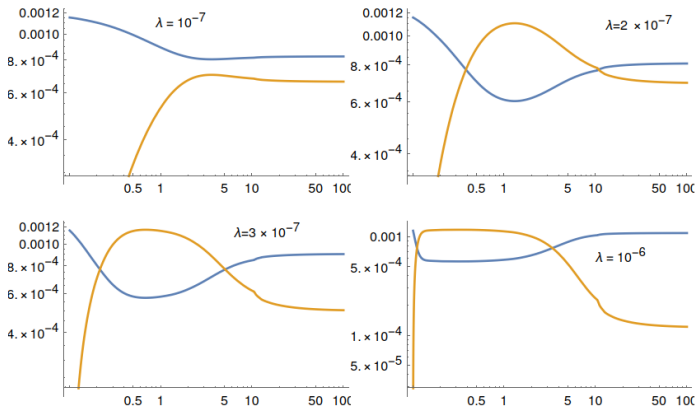
The simplest case to consider is when we have two DMs χ_a and $\chi_b = \chi_c$

$$\frac{1}{a^3} \frac{d(n_{\chi_a} a^3)}{dt} \approx -\langle \sigma v \rangle n_{\chi_a} n_{\psi}$$
$$\frac{1}{a^3} \frac{d(n_{\chi_b} a^3)}{dt} \approx +2\langle \sigma v \rangle n_{\chi_a} n_{\psi}$$

Both number density small



When one is in equilibrium and other one is not



Flip flop behaviour

Summary and concluding remarks

- Exp growth another interesting possibility to explore.
- Although not experimentally tested yet, offers wide range of interesting theoretical avenues.