Conformal Freeze-In of Dark Matter

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(Work in progress with S. Hong, M. Perelstein)

Sept. 27th, Brookhaven Forum 2019
Why?

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➢ What if the thermal history of DM was dominated by a conformal phase?

1. CFT ⇒ No notion of particles possible

2. Large anomalous dimensions ⇒ non-integer operator dimensions
How?

Dark sector phase transition from UV theory (e.g. Banks-Zaks theory) to CFT phase.

\[ \mathcal{L}_{\text{int}} = \lambda_{\text{CFT}} \frac{\mathcal{O}_{\text{SM}} \mathcal{O}_{\text{CFT}}}{\Lambda_{\text{CFT}}^{D-4}} ; \quad D = d_{\text{SM}} + d_{\text{CFT}} \]
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SM interactions and phase transitions (EW/QCD) dynamically generate mass gap. DM production ends.

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- **Reheating temperature**: Only the SM is reheated.
- CFT energy density produced through freeze-in.
- (Only considering scalar operators for now.)
Boltzmann Equations

➤ No particles or number densities ⇒ Use energy density instead!

\[ T^\mu_{\mu} = 0 \Rightarrow P_{\text{CFT}} = \frac{1}{3} \rho_{\text{CFT}} \]

\[ \Rightarrow \frac{\partial \rho_{\text{CFT}}}{\partial t} + 4H \rho_{\text{CFT}} = C \]
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What is the collision term?

Can derive SM $\rightarrow$ CFT term, but for CFT $\rightarrow$ SM, need finite temperature CFT correlators, $\langle O_{\text{CFT}} O_{\text{CFT}} \rangle_T$ : unknown for $D > 2$!
Boltzmann Equations

➢ To ignore backreaction, need $T_{\text{CFT}} \ll T_{\text{SM}}$

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Boltzmann Equations

➢ To ignore backreaction, need $T_{CFT} \ll T_{SM}$

➢ Weak coupling, CFT should not be in thermal equilibrium with the SM

➢ Solution: Freeze-In!

➢ Boltzmann Equation with this assumption:

$$\Rightarrow \frac{\partial \rho_{CFT}}{\partial t} + 4H \rho_{CFT} = n_{SM}^2 \langle \sigma(SM \rightarrow CFT) \nu E_{tot} \rangle$$
Simple Dimensional Analysis

Without calculating the actual collision term, we can predict how the energy density will grow:

\[ n_{\text{SM}}^2 \sim T_{\text{SM}}^6 \ ; \ \langle \sigma v E \rangle \sim \frac{T_{\text{SM}}^{2D-9}}{\Lambda^{2(D-4)}} \]

\[ \Rightarrow C \sim \frac{T_{\text{SM}}^{2D-3}}{\Lambda^{2D-8}} \]

\[ \Rightarrow \rho_{\text{CFT}} \sim T^4 \times \frac{T_{R}^{2D-9} - T_{R}^{2D-9}}{2D - 9} \]

NOT freeze-in for \( D > 4.5 \)
Dark pions have a mass smaller than $m_{\text{gap}}$. SM interactions and phase transitions (EW/QCD) dynamically generate mass gap. DM production ends.
Concrete Example: $\mathcal{O}_{SM} = H^\dagger H$

- Production modes:
  - Above weak scale:
    - Annihilation ($H H \rightarrow \text{CFT}$)
  - Below weak scale:
    - Decay ($H \rightarrow \text{CFT}$)
    - Quark/gluon fusion through Higgs portal ($Q Q / g g \rightarrow \text{CFT}$)

- When SM scale becomes relevant/deformation to CFT is significant, conformality is lost and a mass gap is generated.

\[ m_{\text{gap}} = \left( \frac{v^2}{\Lambda(D-4)} \right)^{\frac{1}{4-d}} \]

e.g. from simple dim. analysis, for $H^\dagger H$, $m_{\text{gap}} = \left( \frac{v^2}{\Lambda(D-4)} \right)^{\frac{1}{4-d}}$
Concrete Example: $\mathcal{O}_{\text{SM}} = H^+ H$

Higgs decay is the most important process in the Higgs scalar operator case.

$T_{\text{CFT}} \ll T_{\text{SM}}$ as required.
Relic Density Plot for $\mathcal{O}_{SM} = H^+ H$

Light keV scale DM!

Note that the WDM bound is weaker for our case.

Typical Higgs portal constraints that are beyond this plot:

- Higgs invisible decay
- Supernova bounds
- Stellar Cooling
- Rare meson decays
Other Constraints

- Direct Detection: DM is too light to be relevant.
- BBN: No $\Delta N_{\text{eff}}$ constraint, as energy in dark sector is very low at BBN.

Work in progress:

1. Beam dump experiments: Similar to rare meson decays; most likely not relevant (more careful check to be completed).
2. CMB distortions.
Conclusions

➢ Possible to have naturally light dark matter candidate!

➢ Non-integral operators in the dark sector’s history

➢ Dynamically generated mass gap: mass is linked to coupling.

➢ Minimal model, with essentially 2 parameters: $d$, and $\frac{m_{\text{gap}}}{m_{\text{DM}}}$

➢ Look out for our paper later this year!
Thank You!