Conformal Freeze-In of Dark Matter

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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
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.

Dark pions have a mass smaller than \( m_{\text{gap}} \).
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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 → CFT term, but for CFT → SM, need finite temperature CFT correlators, \( \langle O_{\text{CFT}} O_{\text{CFT}} \rangle_T \) : unknown for D > 2!
Boltzmann Equations

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➢ Solution: Freeze-In!

➢ Boltzmann Equation with this assumption:

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

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

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

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

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

➢ NOT freeze-in for \( D > 4.5 \)
$m_{\text{gap}}$ → SM interactions and phase transitions (EW/QCD) dynamically generates mass gap. DM production ends.

$m_{\text{DM}}$ → Dark pions have a mass smaller than $m_{\text{gap}}$. 
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.

  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: $\mathcal{O}_{\text{SM}} = H^\dagger H$

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!