Conformal Freeze-In of Dark Matter

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Why?

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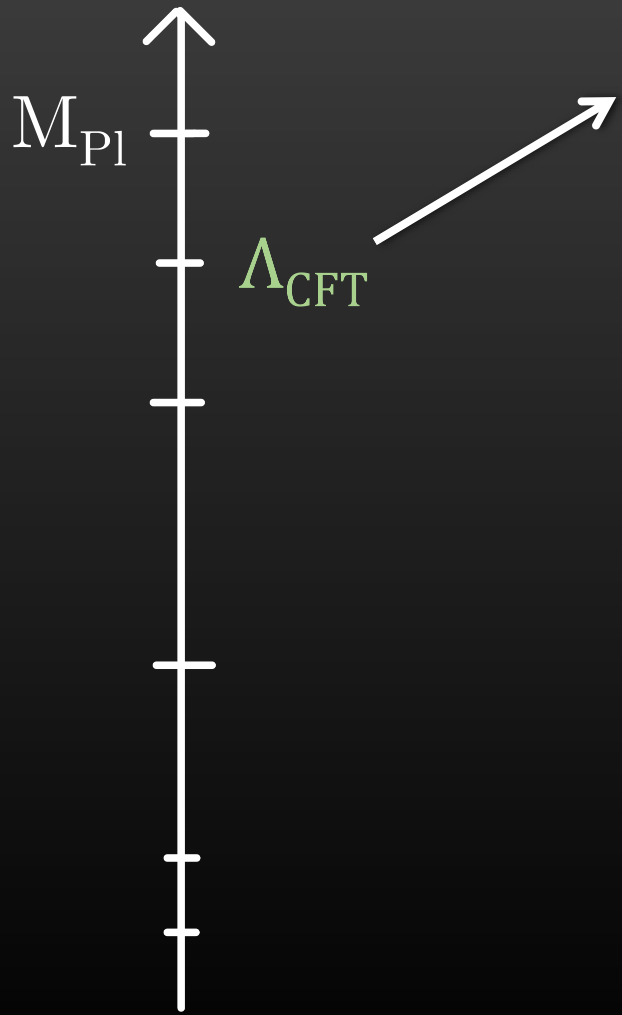
- What if the thermal history of DM was dominated by a conformal phase?

1. CFT $\Rightarrow$ No notion of particles possible
2. Large anomalous dimensions $\Rightarrow$ 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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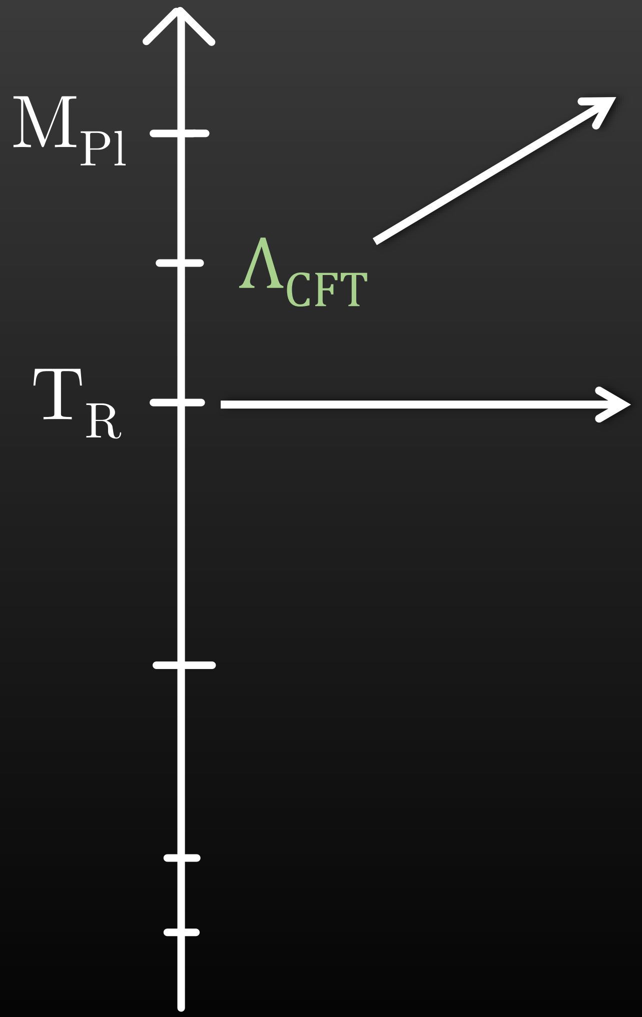

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Reheating temperature: Only the SM is reheated.
CFT energy density produced through freeze-in.

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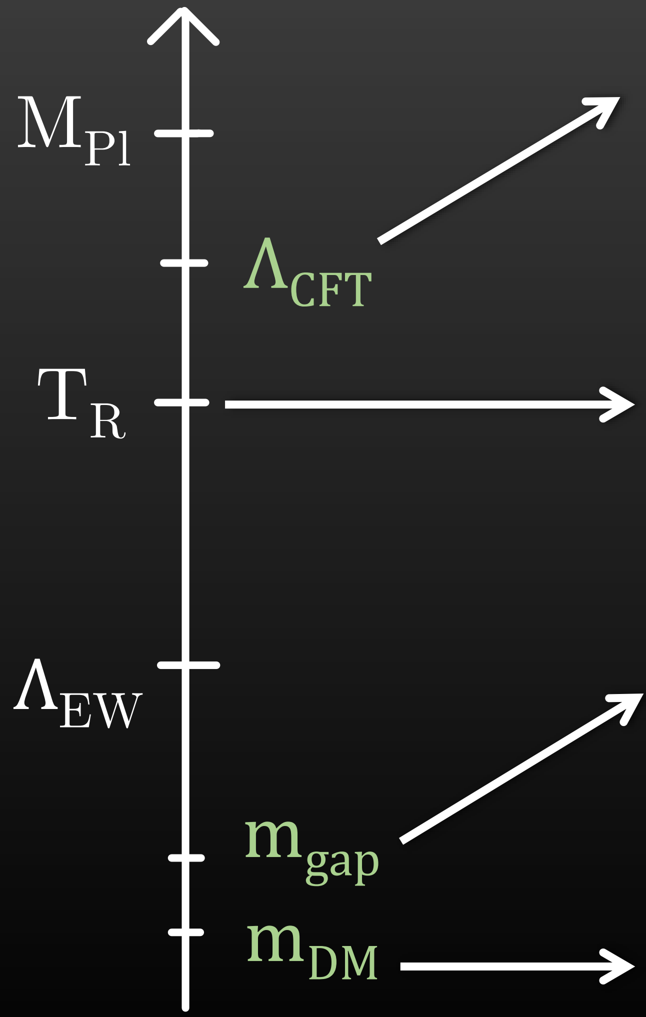

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SM interactions and phase transitions (EW/QCD) dynamically generate mass gap. DM production ends.

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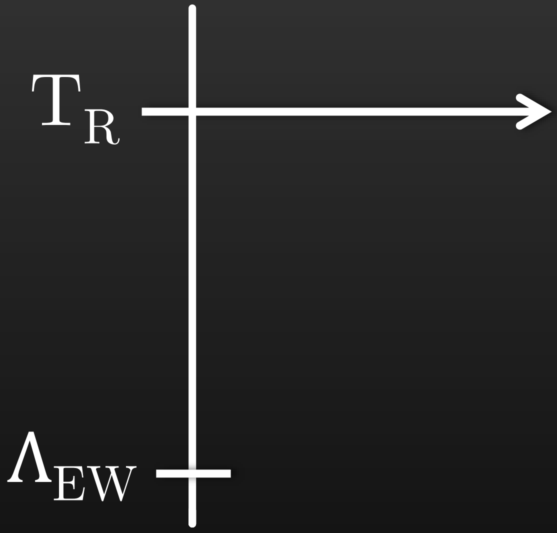

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CFT energy density produced through freeze-in.

(Only considering scalar operators for now.)

Boltzmann Equations

- No particles or number densities $\Rightarrow$ Use energy density instead!

$$T^{\mu}_{\mu} = 0 \Rightarrow P_{\text{CFT}} = \frac{1}{3}\rho_{\text{CFT}}$$

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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, $\langle \mathcal{O}_{\rm CFT}\mathcal{O}_{\rm CFT}\rangle_T$: unknown for D $>$ 2!

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- To ignore backreaction, need $T_{\text{CFT}} \ll T_{\text{SM}}$
- Weak coupling, CFT should not be in thermal equilibrium with the SM
- Solution: Freeze-In!
- Boltzmann Equation with this assumption:

$$\Rightarrow \frac{\partial \rho_{\text{CFT}}}{\partial t} + 4H\rho_{\text{CFT}} = n_{\text{SM}}^2 \langle\, \sigma(\text{SM} \to \text{CFT})\; v\; E_{tot}\, \rangle$$

Simple Dimensional Analysis

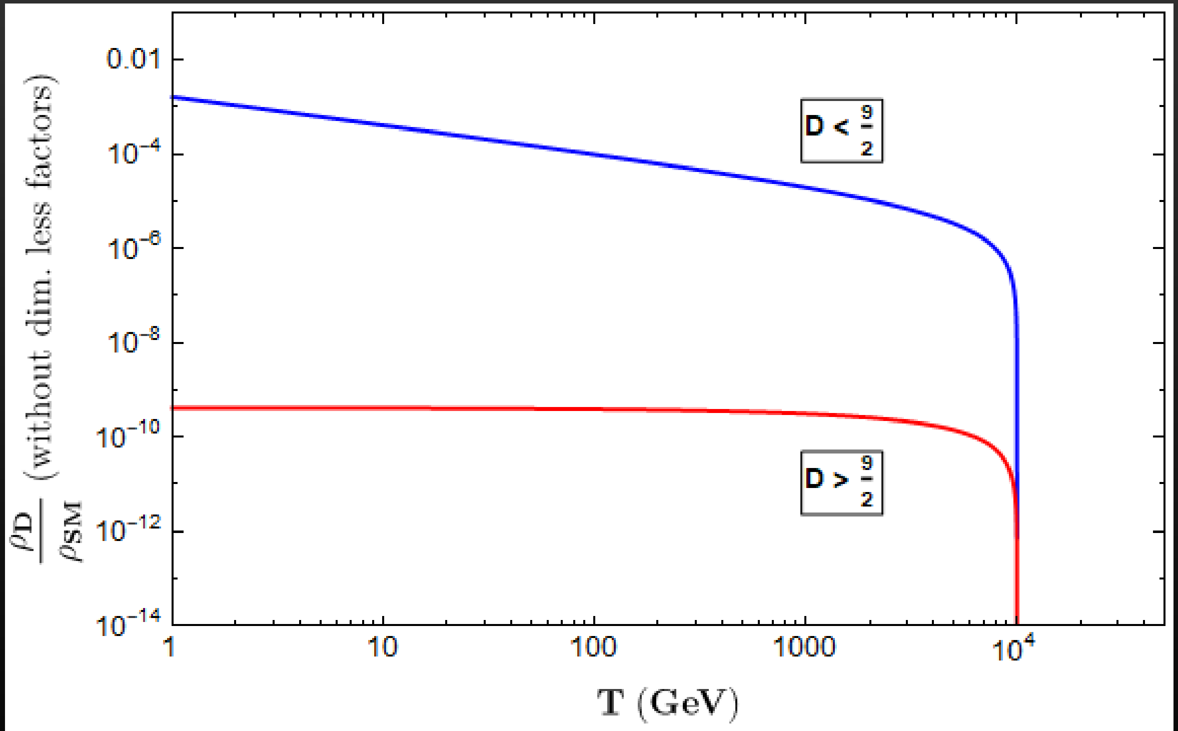
- Without calculating the actual collision term, we can predict how the energy density will grow:

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

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

$$\Rightarrow \rho_{\rm CFT} \sim T^4 \times \frac{T_R^{2D-9} - T^{2D-9}}{2D-9}$$

- <u>NOT</u> freeze-in for D > 4.5



m_{gap} → SM interactions and phase transitions (EW/QCD) dynamically generates mass gap. DM production ends.

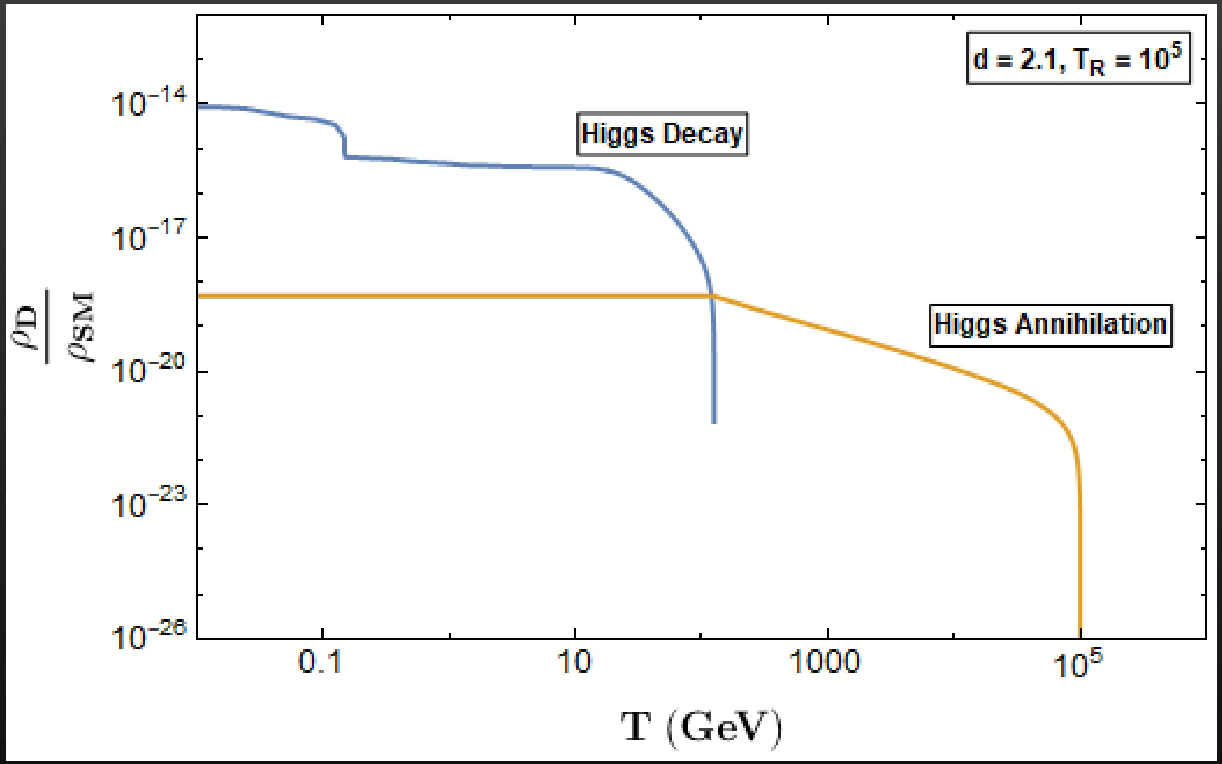
m_{DM} → Dark pions have a mass smaller than m_{gap}.

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

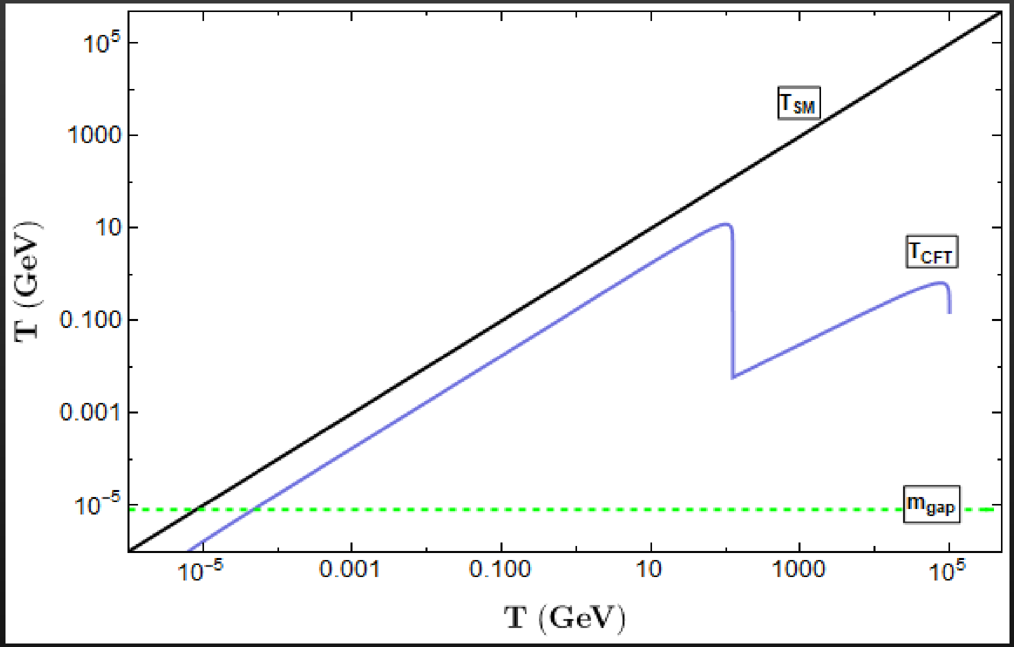
- Production modes:
  - → Above weak scale:
    - ¤ Annihilation (H H → CFT)
  - → Below weak scale:
    - ¤ Decay (H → CFT)
    - ¤ Quark/gluon fusion through Higgs portal (Q Q / g g → CFT)
- When SM scale becomes relevant/deformation to CFT is significant, conformality is lost and a mass gap is generated.

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

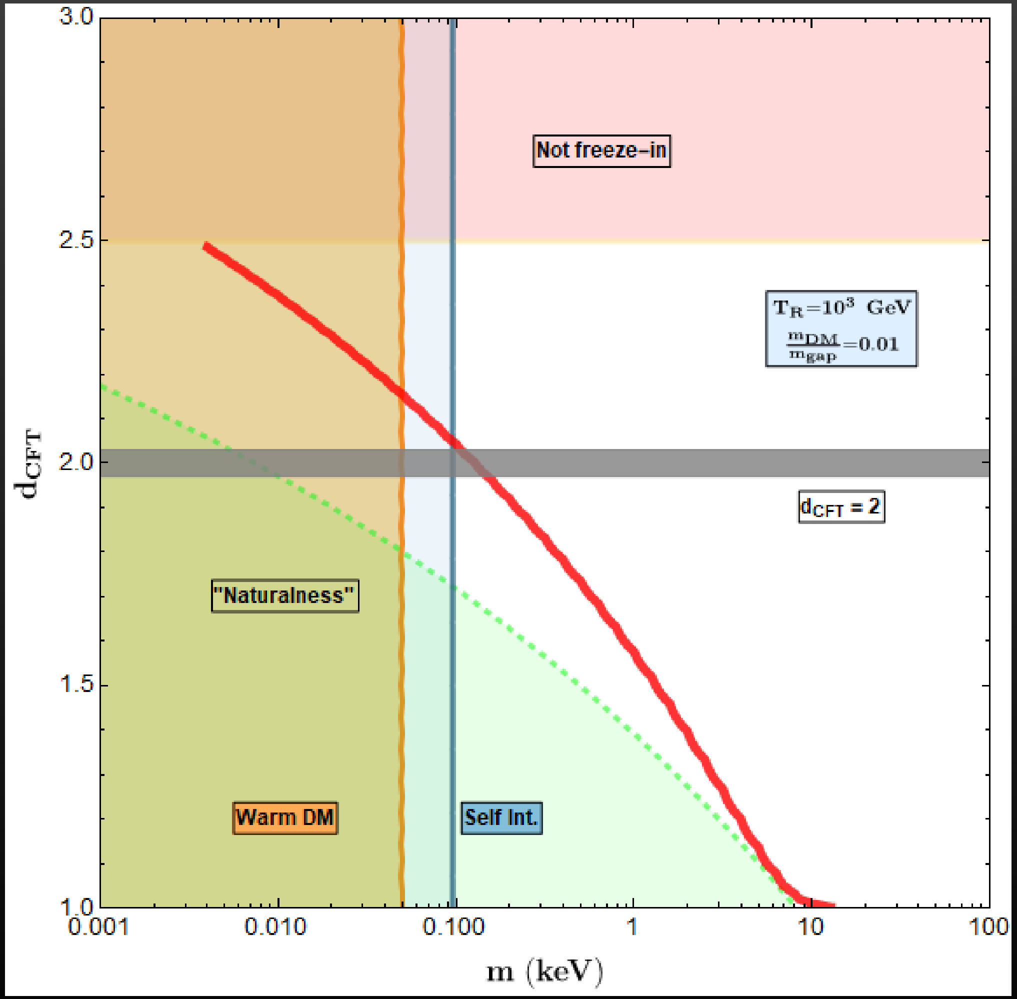


Higgs decay is the most important process in the Higgs scalar operator case.



$T_{\rm CFT} \ll T_{\rm SM}$ as required.

Relic Density Plot for $\mathcal{O}_{\rm SM} = \rm H^\dagger H$



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 ΔN_{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!