Conformal Freeze-In of Dark Matter

Gowri Kurup

Rudolf Peierls Centre for Theoretical Physics

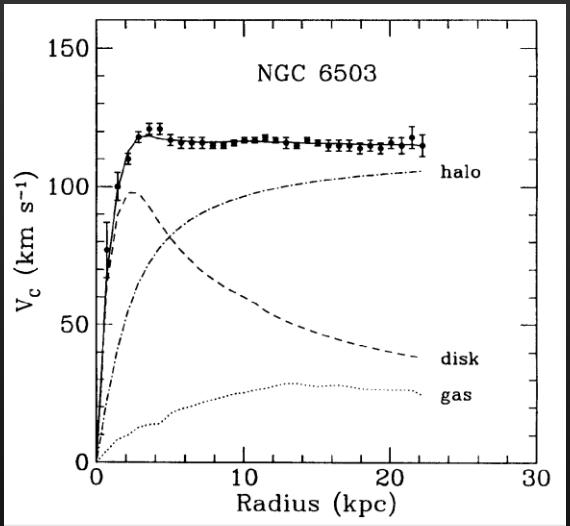
UNIVERSITY OF OXFORD

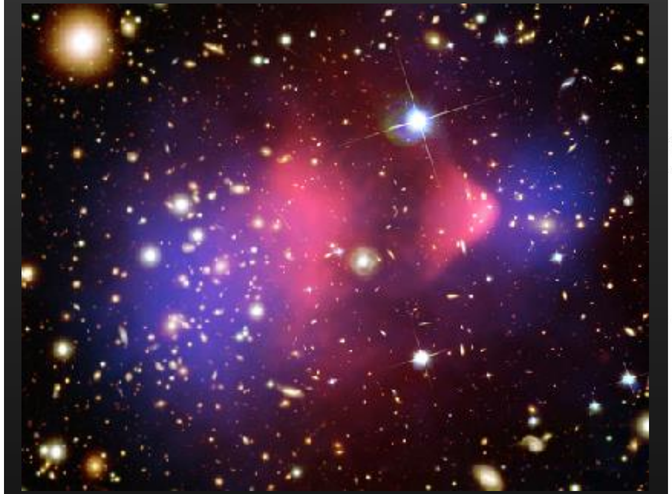
Dark Interactions

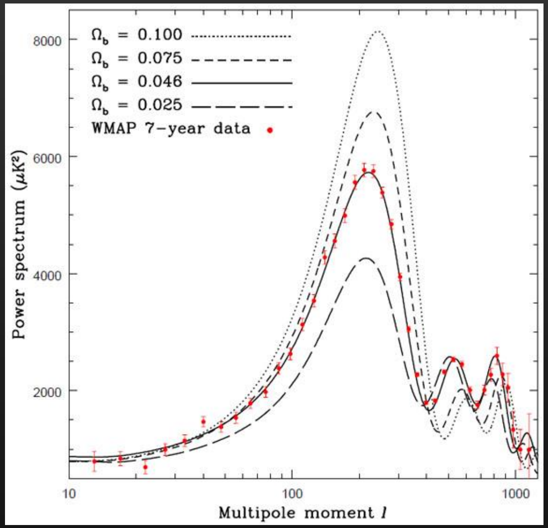
November 2022

What is Dark Matter?

We have lots of evidence through gravitational interactions:







But its microscopic nature is completely unknown.

Why Conformal Freeze-In (“COFI”)?

S. Hong, G. Kurup and M. Perelstein [arXiv: 1910.10160, 2207.10093]

- Models so far – based on assumption of particle nature of DM.

Why Conformal Freeze-In (“COFI”)?

S. Hong, G. Kurup and M. Perelstein [arXiv: 1910.10160, 2207.10093]

- Models so far – based on assumption of particle nature of DM.
- What if the thermal history of DM was dominated by a conformal phase?

Why Conformal Freeze-In (“COFI”)?

S. Hong, G. Kurup and M. Perelstein [arXiv: 1910.10160, 2207.10093]

- Models so far – based on assumption of particle nature of DM.
- 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.
    3. Naturally light DM in this scenario (as we will see later).

Why Conformal Freeze-In ("COFI")?

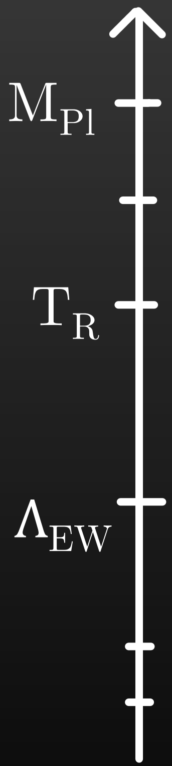
S. Hong, G. Kurup and M. Perelstein [arXiv: 1910.10160, 2207.10093]

- Models so far – based on assumption of particle nature of DM.
- What if the thermal history of DM was dominated by a conformal phase?

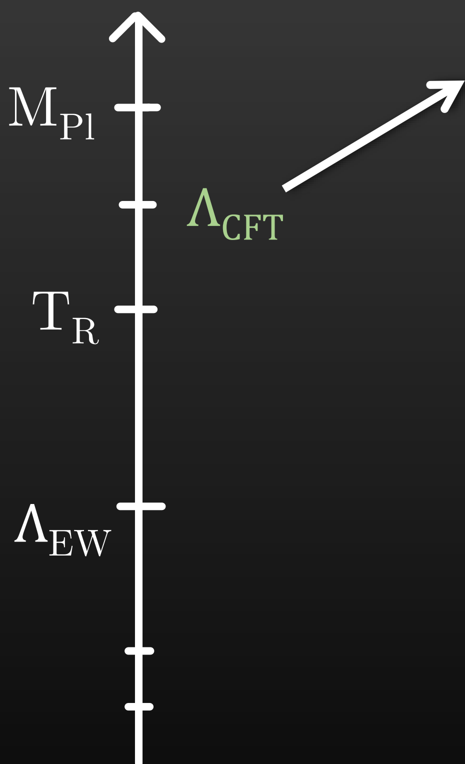
    1. CFT $\Rightarrow$ No notion of particles possible.
    2. Large anomalous dimensions $\Rightarrow$ non-integer operator dimensions.
    3. Naturally light DM in this scenario (as we will see later).

- Dark sectors with (approximate) conformal symmetry (that produce observed relic abundance) can be shown to undergo **freeze-in**, with minimal assumptions.

Basic Setup



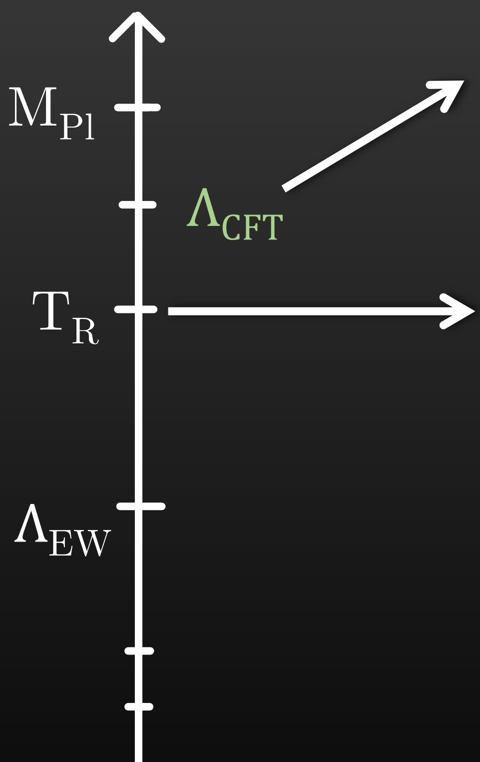
Basic Setup



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

$$\mathcal{L}_{\text{int}} = \lambda_{\text{CFT}} \frac{\mathcal{O}_{\text{SM}} \mathcal{O}_{\text{CFT}}}{\Lambda_{\text{CFT}}^{D-4}} \; ; \quad D = d_{\text{SM}} + d_{\text{CFT}}$$

Basic Setup

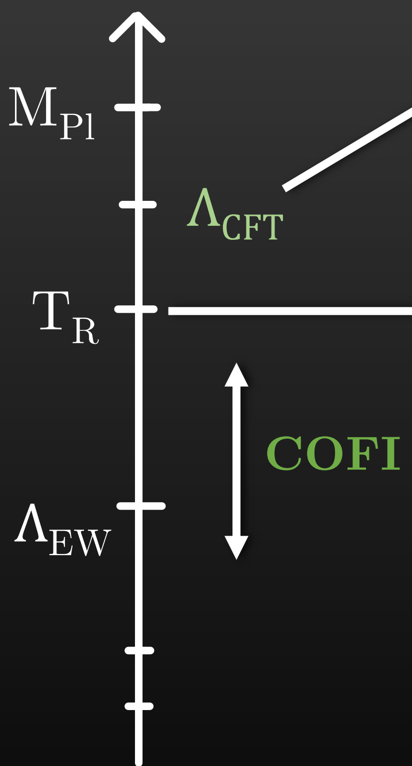


Dark sector phase transition from UV theory (e.g. Banks-Zaks theory) to CFT phase.

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT}\, \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}}\ ; \quad D = d_{\rm SM} + d_{\rm CFT}$$

Reheating temperature: Only the SM is reheated. CFT energy density production can start.

Basic Setup

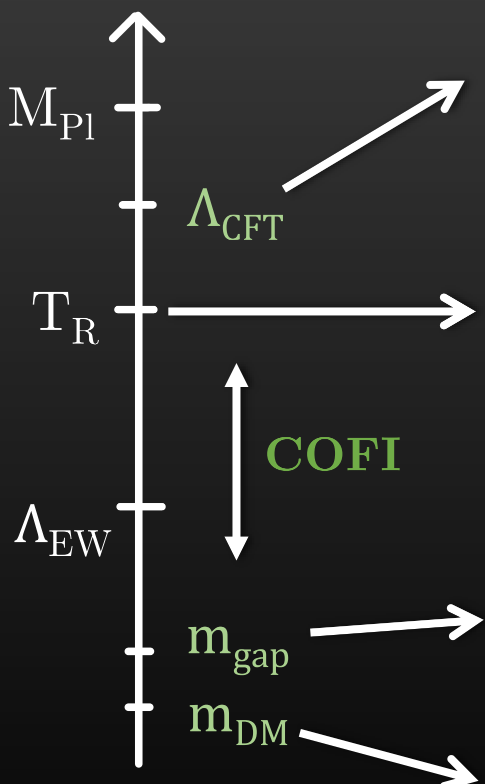


Dark sector phase transition from UV theory (e.g. Banks-Zaks theory) to CFT phase.

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT} \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \; ; \quad D = d_{\rm SM} + d_{\rm CFT}$$

Reheating temperature: Only the SM is reheated. CFT energy density production can start.

Basic Setup



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

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT} \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \; ; \qquad D = d_{\rm SM} + d_{\rm CFT}$$

Reheating temperature: Only the SM is reheated. CFT energy density production can start.

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

Dark pions (DM) have a mass smaller than m_{gap}, with $r \equiv m_{DM} / m_{gap}$

Boltzmann Equations

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

$$\text{Isotropy} \; + \; \text{Homogeneity} \Rightarrow$$

$$T^{\mu\nu}_{\text{CFT}} = \begin{pmatrix} \rho_{\text{CFT}} & 0 & 0 & 0 \\ 0 & P_{\text{CFT}} & 0 & 0 \\ 0 & 0 & P_{\text{CFT}} & 0 \\ 0 & 0 & 0 & P_{\text{CFT}} \end{pmatrix}$$

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

Boltzmann Equations

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

$$\Rightarrow \frac{\partial \rho_{\rm CFT}}{\partial t} + 4H\rho_{\rm CFT} = \boxed{C}$$

What is the collision term?

SM $\rightarrow$ CFT terms*: e.g. for 2 $\rightarrow$ CFT, $n_{\rm SM}^2 \langle\, \sigma(\text{SM} \rightarrow \text{CFT})\, v\, E_{tot}\, \rangle$

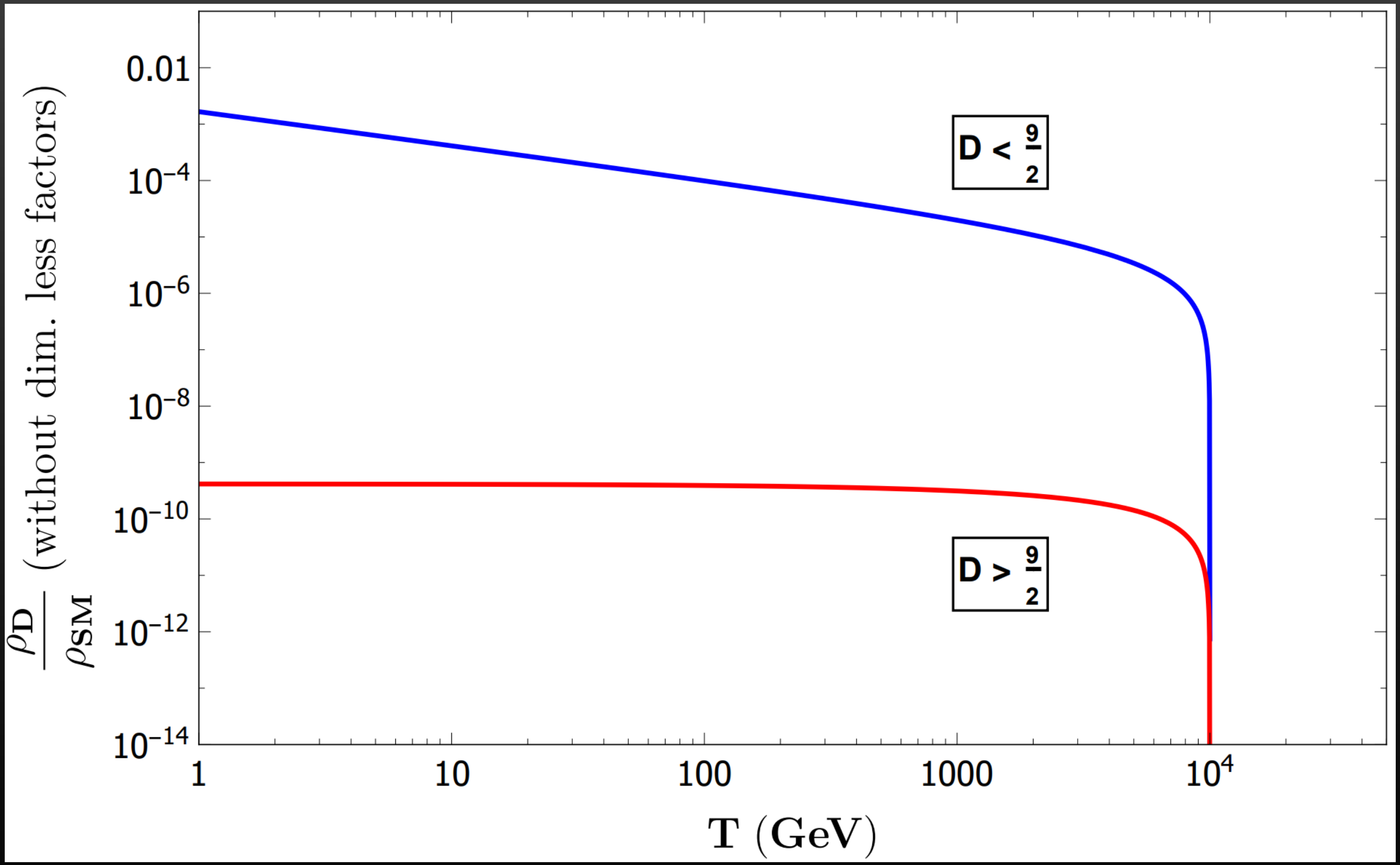
CFT $\rightarrow$ SM: need finite temperature CFT correlators, $\langle \mathcal{O}_{\rm CFT}\mathcal{O}_{\rm CFT}\rangle_T$, which are difficult to calculate.

*See H. Georgi [arXiv:hep-ph/0703260v3]

Boltzmann Equations

- Freeze-in $\rightarrow$ ignore backreaction, $T_{\rm D} \ll T_{\rm SM}$.
- Weak coupling $\rightarrow$ CFT is never in thermal equilibrium with the SM.
- Implicit assumption: CFT is strongly coupled, and thermalizes very quickly compared to Hubble; in thermal equilibrium with temperature T_D.

COFI: UV vs IR Production



Generation of mass gap

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT} \, \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \; ; \quad D = d_{\rm SM} + d_{\rm CFT}$$

When a relevant deformation to the CFT (due to $\mathcal{O}_{\rm SM}$) is produced, conformal symmetry is broken and a mass gap is generated.

Generation of mass gap

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT} \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \; ; \quad D = d_{\rm SM} + d_{\rm CFT}$$

When a relevant deformation to the CFT (due to $\mathcal{O}_{\rm SM}$) is produced, conformal symmetry is broken and a mass gap is generated.

Types of deformations:

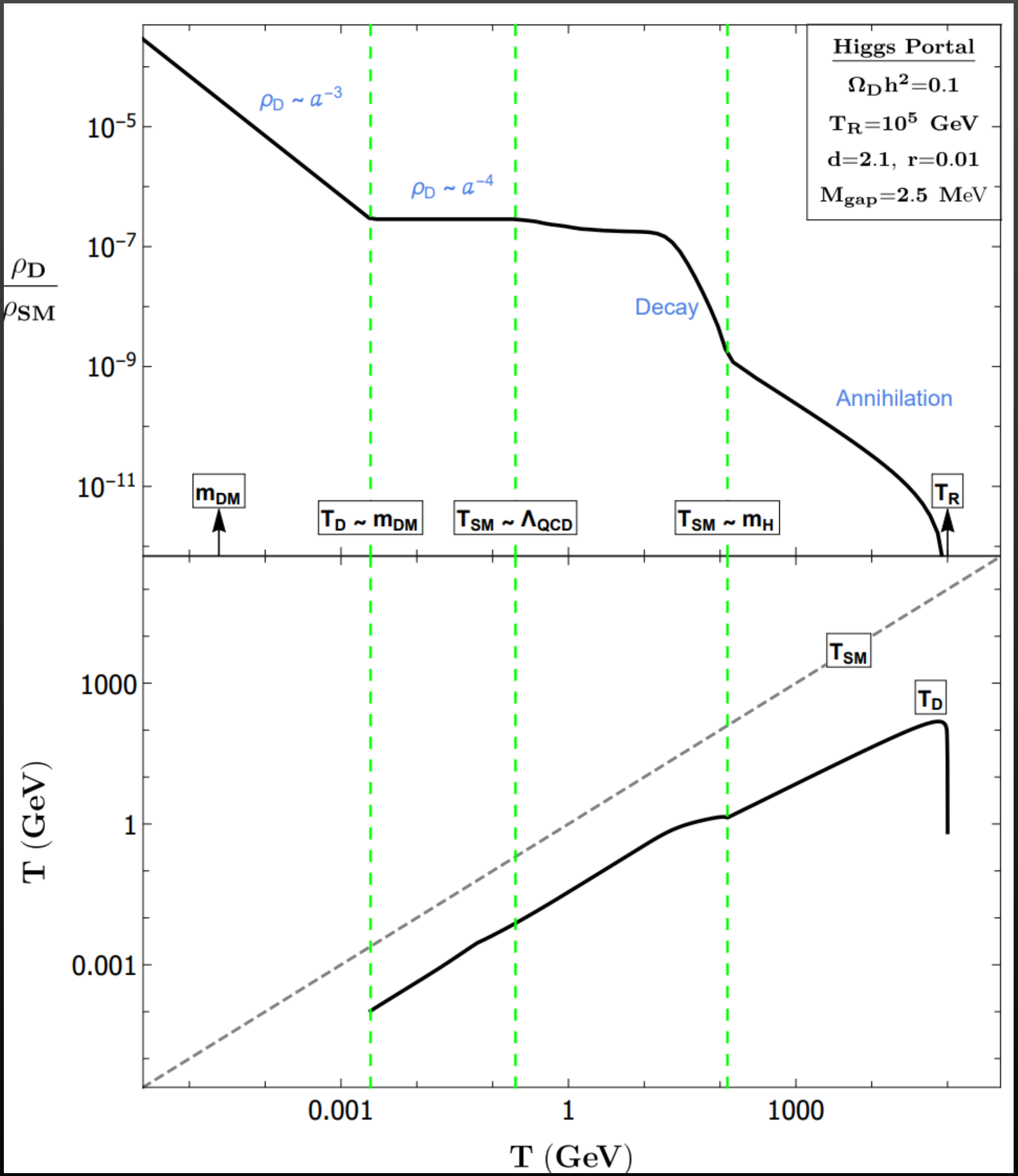
1. Generation of $\mathcal{O}_{\rm CFT}$ due to $\mathcal{O}_{\rm SM}$ getting a VEV,
2. Generation of $\mathcal{O}_{\rm CFT}$ due to loop induced coupling to other SM operators with a VEV,
3. Generation of $\mathcal{O}_{\rm CFT}$ due to SM loops,
4. Generation of $\mathcal{O}_{\rm CFT}^2$ due to loops with SM particles.

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

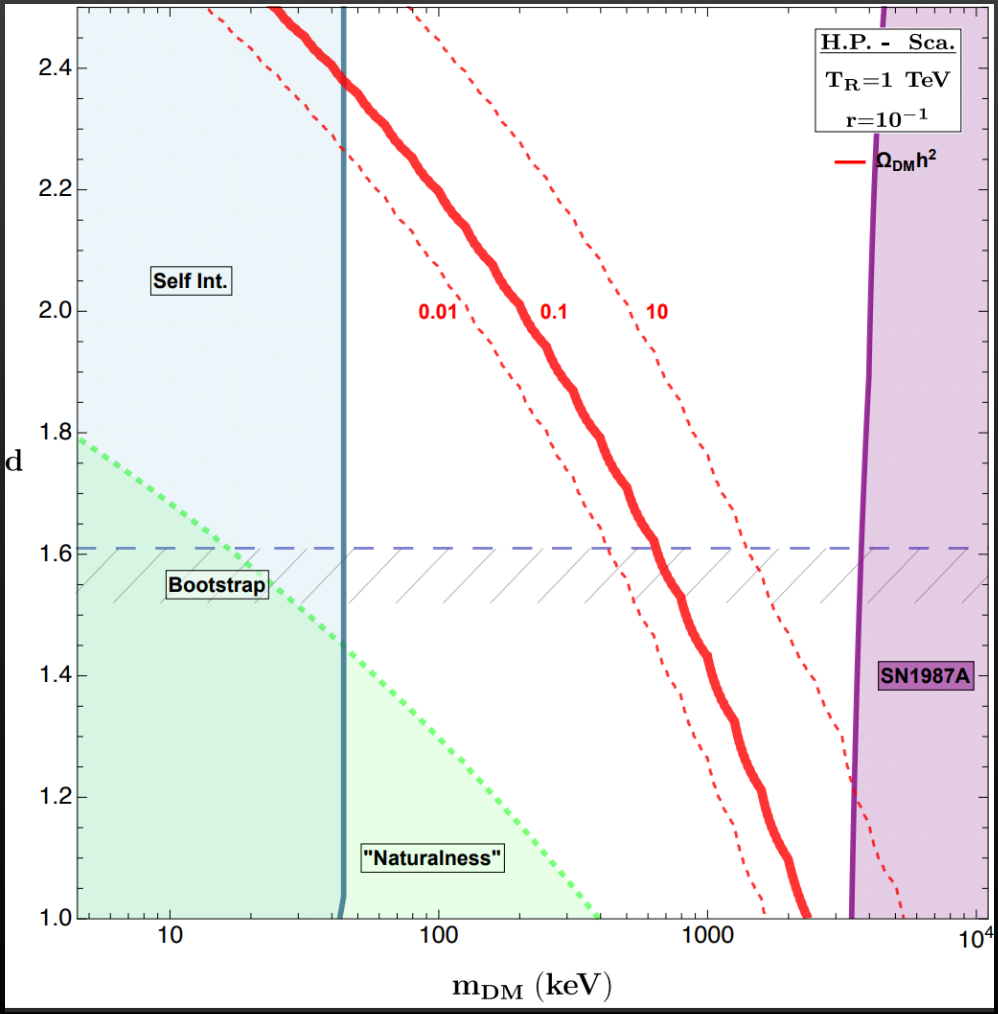
- Production modes:
  - $\longrightarrow$ Above weak scale:
    - ¤ Annihilation (H H $\rightarrow$ CFT)
  - $\longrightarrow$ Below weak scale:
    - ¤ Decay (H $\rightarrow$ CFT)
    - ¤ Quark/gluon fusion through Higgs portal (q q / g g $\rightarrow$ CFT)
- Production ends at $\Lambda_{\rm QCD}$
- DM becomes non-relativistic as temperature of dark sector falls below mass.

$$m_{\rm DM} = r \times \left(\frac{\lambda_{\rm CFT}\, v^2}{\Lambda_{\rm CFT}^{d-2}} \right)^{\frac{1}{4-d}}$$

- Higgs decay dominates for $d < d^* = 2.5$.
- Quark/gluon annihilations are negligible
- $T_D \ll T_{SM}$ as required.
- Redshift as matter (a^{-3}) for T_D below mass of DM.



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



- With r = 0.1,
  Light 0.1 – 1 MeV scale DM!
- Higher masses:
  Overproduction of DM
- Mass and coupling are one-to-one related.
- Higher r: Self interaction constraints
- Lower r: Warm DM constraints

All Portals Studied:

$\mathcal{O}_{\rm SM}$	DM Mass (Scalar Mediator)	DM Mass (Vector Mediator)	Dominant CFT Deformation	Dominant Production Mode
$H^\dagger H$	0.4 - 1.2 MeV	40 - 400 keV	Tree-level	$h \to$ CFT
$HQ^\dagger q$	1st: ~~SN~~ All: 0.1 - 1 MeV MFV: 0.5 - 5 MeV	1st: ~~SN~~ All: 50 - 200 keV MFV: 0.1 - 1 MeV	Radiative mixing	$q\bar{q} \to$ CFT
$HL^\dagger \ell_R$	1st: 0.5 - 5 keV All: 1 - 10 keV MFV: 10 - 100 keV	1st: ~~WDM~~ All: ~~WDM~~ MFV: 0.5 - 5 keV	Radiative mixing	$\ell\bar{\ell} \to$ CFT
$G^{\mu\nu}G_{\mu\nu}$	0.2 - 2 MeV	50 - 400 keV	Radiative direct	$gg \to$ CFT
$B^{\mu\nu}B_{\mu\nu}$	0.1 - 10 MeV	0.05 - 1 MeV	Radiative direct	$\gamma\gamma \to$ CFT

Summary

- Naturally light dark matter candidate from COFI
- keV-MeV dark matter masses for all portals considered
- 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 $\frac{m_{\text{gap}}}{m_{\text{DM}}}$

See arXiv:1910.10160 for some details, and stay tuned for the follow-up paper!

Thank you!

EXTRAS!

Basic Setup

Consider a scale-invariant dark sector coupled to the SM as,

$$\mathcal{L}_{\rm int} = \lambda_{\rm CFT} \, \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \; ; \quad D = d_{\rm SM} + d_{\rm CFT}$$

with $\lambda_{\rm CFT} \ll 1$:

- Expected from a Banks-Zaks theory in UV point-of-view.
- Conformal Symmetry breaking is small, and technically natural.
- $\Lambda_{\rm CFT}$ is the cut-off scale for the CFT, above which it should be replaced with a UV theory.
- Only consider scalar operators for this scenario, for e.g.

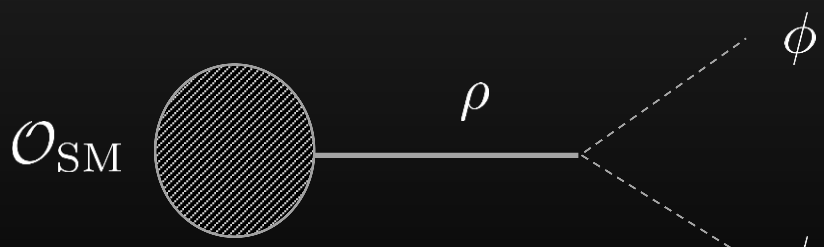
$$\mathcal{O}_{\rm SM} = H^\dagger H,\ HQ_L^\dagger q_R,\ HL^\dagger l_R,\ G^{\mu\nu}G_{\mu\nu}$$

The Confined Phase

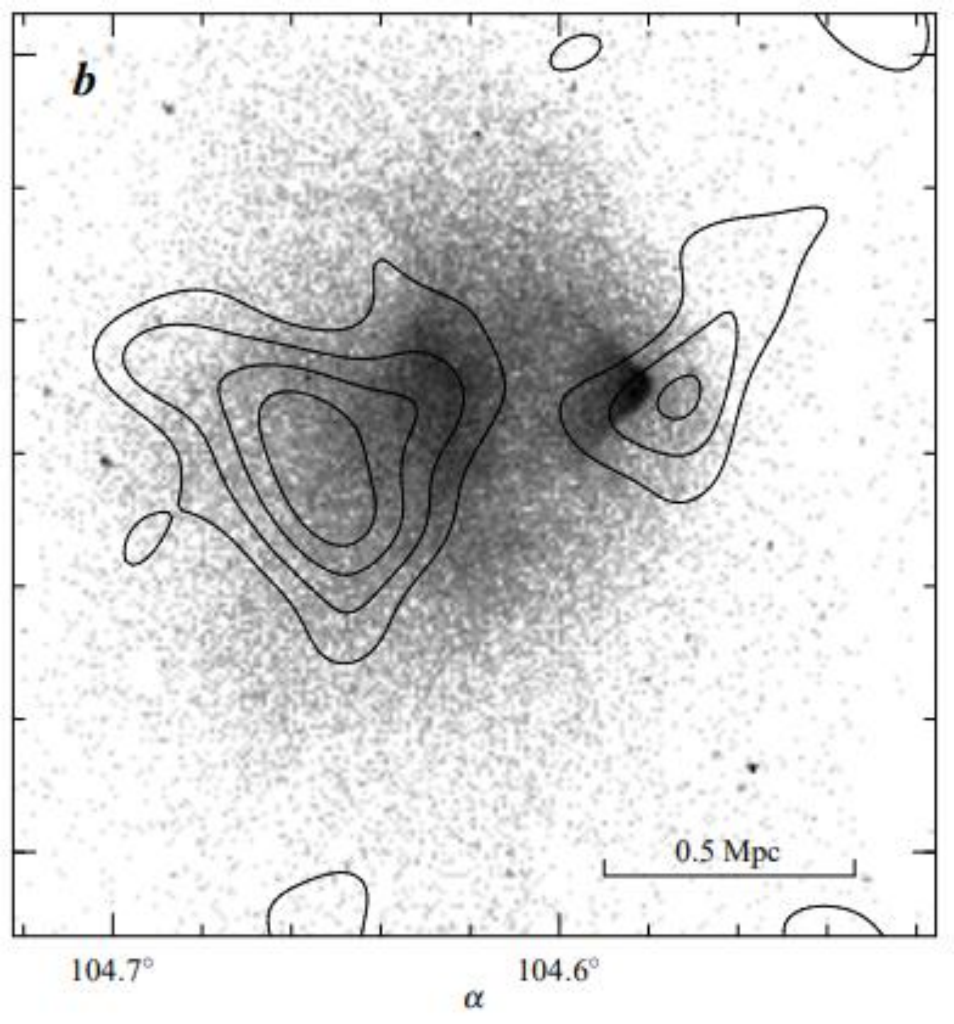
- After a mass gap is generated, we expect particles of mass $\sim m_{gap}$.

- Take DM to be PGB of an approximate global symmetry spontaneously broken at m_{gap}. (Compare with pions.)

- There can be many hadronic states, but to be model-agnostic, we consider a mediator to the dark sector ρ at m_{gap} and the DM to be the lightest state that it decays to prominently, ϕ.



Let’s look at the constraints...



M. Markevitch et al., Astrophys. J. 606, 819 (2004)

Self-Interaction Bounds

Bound from bullet cluster and other galaxy cluster mergers:

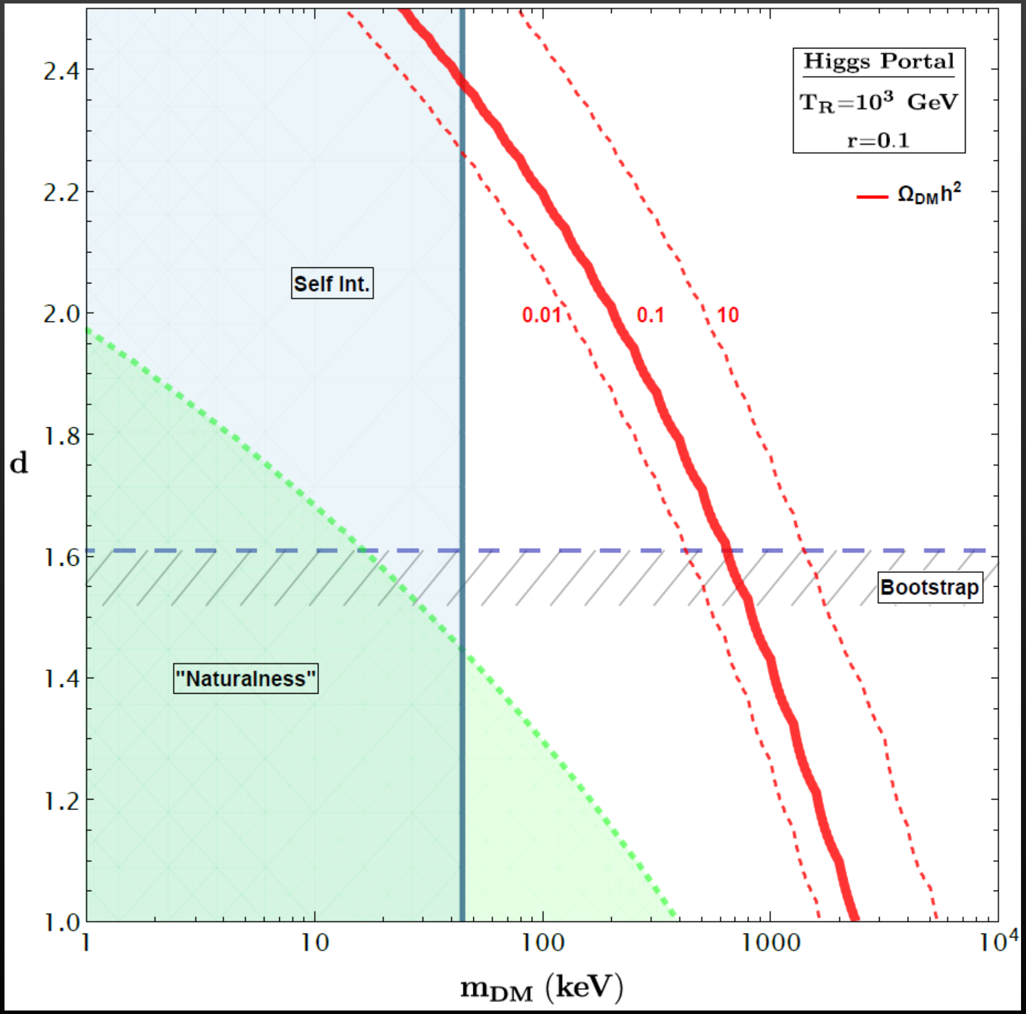
$$\frac{\sigma_{self}}{m} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

For PGB Dark Matter, derivative couplings imply,

$$\sigma_{self} \sim \frac{m_{\mathrm{DM}}^6}{8\pi m_{gap}^8} = \frac{r^6}{8\pi m_{gap}^2}$$

Overlay of the weak lensing mass contours on the X-ray image of galaxy cluster 1E 0657–56. The gas bullet lags behind the DM subcluster.

Let's look at the constraints...

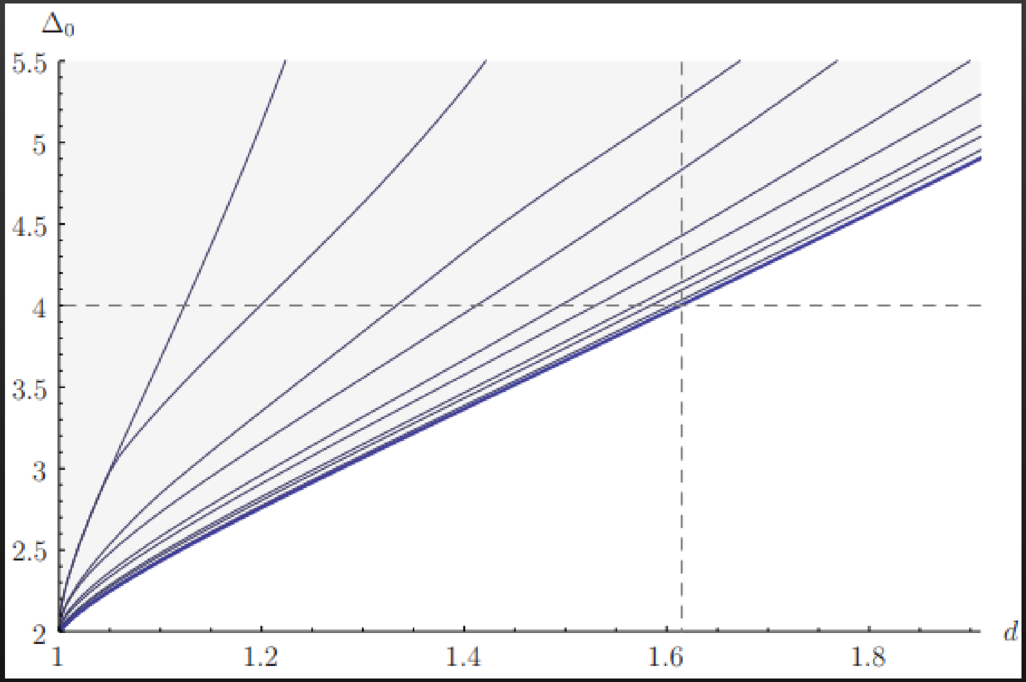


" Naturalness "

With $\lambda_{BZ} \sim 1$, we want to have $M_{BZ} < M_{pl}$.

But this is a model-dependent constraint that depends on choice of T_R and d_{BZ}.

Let’s look at the constraints...



Upper bounds on scaling of lowest dimension scalar in ϕ x ϕ. Different curves are for different numbers of functionals.

D.Poland, D.Simmons-Duffin and A.Vichi, [arXiv:1109.5176 [hep-th]]

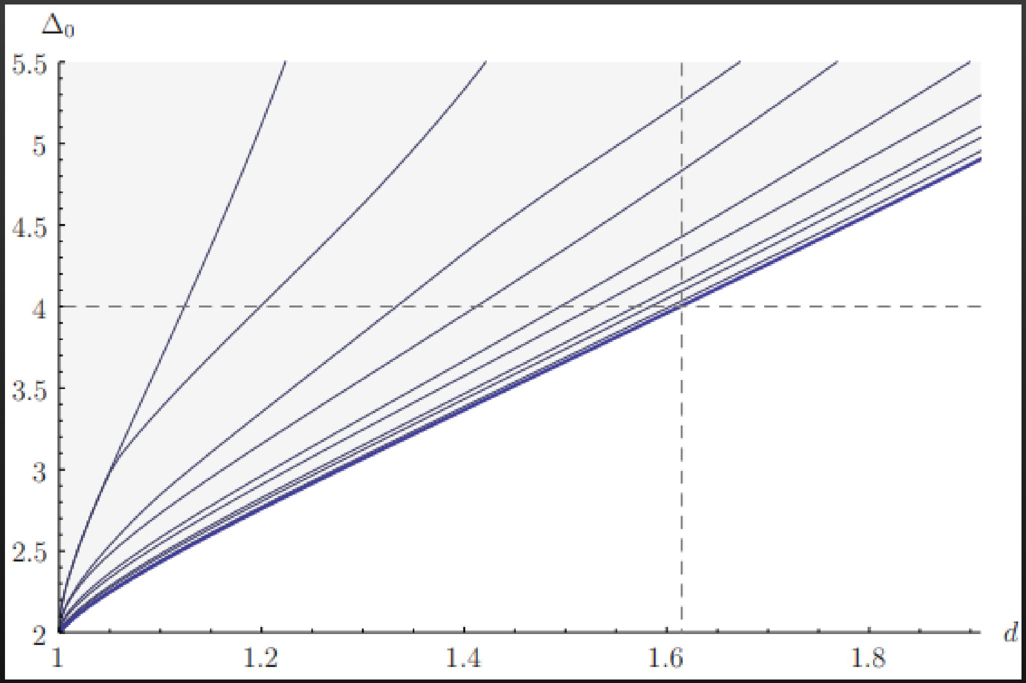
<u>CFT Bootstrap</u>

CFT Bootstrap is a method by which OPE (Operator Product Expansion) coefficients are constrained using symmetries.

For COFI to work, we need to avoid relevant UV deformations of the CFT.

(Otherwise, mass gap is generated in the UV)

Let's look at the constraints...



Upper bounds on scaling of lowest dimension scalar in ϕ x ϕ. Different curves are for different numbers of functionals.

D.Poland, D.Simmons-Duffin and A.Vichi, [arXiv:1109.5176 [hep-th]]

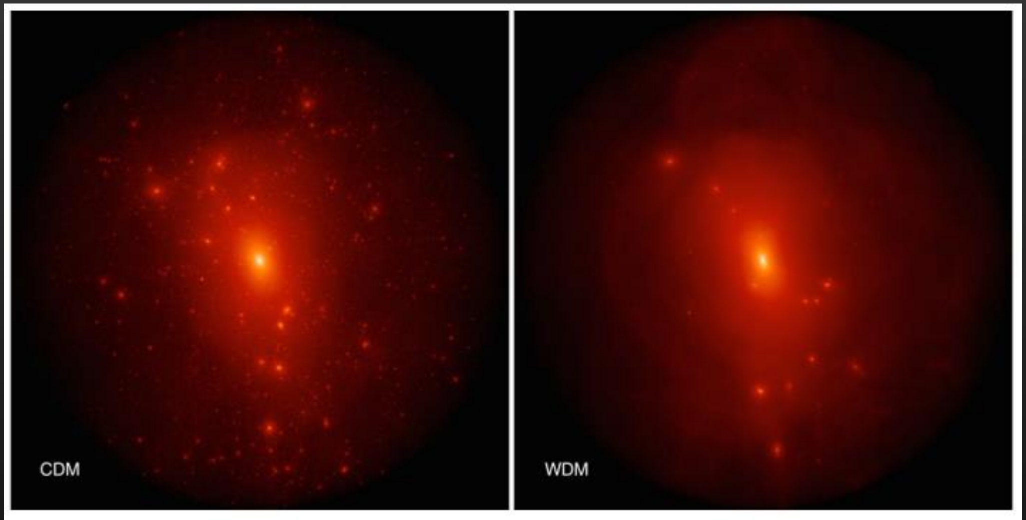
CFT Bootstrap

Solution: assume symmetries to avoid relevant operators in CFT Lagrangian.

E.g.- If we assume a Z_2 symmetry for the CFT operator, there can be relevant singlet deformations in the UV to be a consistent CFT. There are upper bounds on this from the ϕ x ϕ OPE, and this gives *(model-dependent)* bounds on d.

Solutions: Higher symmetry/ fine-tuning

Let's look at the constraints...



N-body simulations of galactic haloes in universes dominated by CDM (left) and WDM (right; for a particle mass of 2 keV).

M. Drewes *et. al.* [arXiv:1602.04816 [hep-ph]]

Warm DM Bound

For thermal DM, any mass < 5 keV $\Rightarrow$ structure formation is disrupted.

For COFI:

$$T_{\mathrm{D}} \ll T_{\mathrm{SM}} \Rightarrow$$

$$m_{\mathrm{DM}} \gtrsim 5 \text{ keV} \times \left.\frac{T_{\mathrm{D}}}{T_{\mathrm{SM}}}\right|_{T_{\mathrm{SM}} \sim \Lambda_{QCD}}$$

Other Constraints

- Direct Detection: DM is too light and weakly coupled to be relevant.
- BBN: No ΔN_{eff} constraint, as energy in dark sector is very low at BBN.
- Deviation in CMB observables from changing ionization history
- Diffuse X- and Gamma-ray backgrounds
- Invisible rare meson decays
- Beam dump experiments

Coupling to SM is too small, and constraints are negligible.

Other Constraints

- Specific to $H^\dagger H$: Higgs invisible decay
- Specific to $HQ^\dagger q_R$: Collider searches for $q\ q \to$ 'unparticles'
- Specific to $HL^\dagger l_R$: LEP searches for $e^+ e^- \to$ MET + γ

→ Irrelevant as well, due to weak coupling.