Dark Matter from a Conformal Dark Sector

[Work with Sungwoo Hong and Gowri Kurup, 2207.10093, JHEP and w/Sungwoo Hong and Taewook Youn, 2412.00181 and w/Lillian Luo, 2412.xxxxx]

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- Conformal field theories seem ubiquitous, appear at interacting fixed points of RG flows operator. Generally the CFT is strongly the CFT is strongly coupled, and depended in the coupled of th
- (below some UV cutoff >> weak scale)
- Can dark matter arise from such a DS? $\frac{1}{2}$ from such a DS?
- Conformal symmetry fixes scaling of CFT energy density in FRW universe: $\rho \propto a^{-4}$
- However DS is generically coupled to the SM, which is not conformal is generically coupled to the SM,
conformal
- This may produce an interesting DM candidate $\mathcal{L}_{\mathcal{F}}$

Conformal(-ish) Dark Sector 2.1 Conformal Dark Sector

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

In a generic theory (such as QCD), both vector and scalar mesons will be present with is a scalar operator with scaling dimension *d*. Once the CFT confines, it is expected to "interpolate" a scalar operator made up of canonically normalized field operators of composite where $M_{\rm BHZ}$ is the UV cuto $M_{\rm BHZ}$ is the gauge theory, BZ is the gauge theory, BZ is the coupling and is a fermion of the gauge theory, BZ is the coupling and is a fermion of the coupling and is a fermion of the coup $\mathcal{M}_{\mathbf{P7}}$

subdominant in the low-energy e $\mathcal{L}_{\mathcal{A}}$ the e↵ective dimension with more suppression by inverse powers of *M*gap, rendering them subdominant in the low-energy e↵ective theory.

• In the deep UV, dark sector is a gauge theory, coupled to SM e.g. via theories with fixed points in the infrared *a la* Banks-Zaks [16, 17].³ In the UV, an operator leep UV, dark sector is a gauge theory, the deep UV, dark sector is a gauge theory, coupled to SM e.g. via \blacksquare In the deep LIV dark sector is a gauge theory coupled to SM e.g. via under *G*.

- DS flows to an interacting IR fixed point (Banks-Zaks) at $\, \Lambda_{\rm CFT}^{} < M_{\rm BZ}$ in the UV. We impose BZ \sim O(1) as a natural new condition in all the models we condition in all the models w
The models we consider the models we consider the models we consider the models were considered with the model corresponds to the original operator of the gauge theory. The matching for the example of a icting IR fixed point (Banks-Zaks) at $\, \Lambda_{\rm CFT} \, < \, M_{\rm BZ}$ $\sqrt{1/\ln n}$ $\sum_{\mathbf{k}}$ is a fixed point and the UV gauge theory has a phase transition into the (generalically strongly coupled) conformal phase. *O*CFT is the operator in the conformal phase that t_{H} is the infrared points in the infrared t_{H} and t_{H} . In the UV, and τ \sim to an interacting in mode point (Banne Lare) at $\Lambda_{\text{CFT}} \sim \frac{1}{4}$ some scale flows to an interacting IR fixed point (Banks-Zaks) at $\Lambda_{\text{cusp}} \leq M_{\text{BZ}}$ Γ • DS flows to an interacting in fixed point (Banks-Zaks) B at A .
CFT [.] \mathbf{F}^{\top}
	- Below $\Lambda_{\rm CFT}$, the dark sector is a CFT, coupled to SM via be *SU*(*N*) and also we do not require the fixed point to be weakly interacting. λ_{CFT} $\Lambda^{D-4}_{\scriptscriptstyle\rm CFT}$ CFT $\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT} \qquad \qquad \lambda_{\rm CFT} \approx \lambda_{\rm BZ} \left(\frac{\Lambda_{\rm CFT}}{M_{\rm BZ}}\right)^c$ $\lambda_{\text{CFT}} \approx \lambda_{\text{BZ}} \left(\frac{P_{\text{CFT}}}{M_{\text{BZ}}} \right)$ $D = d + d_{\text{SM}}$ dark sector is never in equilibrium with the Standard Model, and dark sector energy density of α $\frac{1}{2}$ is produced through the freeze-in mechanism. In the next show that the next section, we will show the next show that $\frac{\mathrm{FT}}{\mathrm{N}_{\mathrm{CFT}}} \mathcal{O}_{\mathrm{SM}} \mathcal{O}_{\mathrm{CFT}} \qquad \qquad \lambda_{\mathrm{CFT}} \approx \lambda_{\mathrm{BZ}} \Big(\frac{\Lambda_{\mathrm{CFT}}}{M}\Big)^{d_{\mathrm{SM}}-1} \qquad \qquad D=d+d_{\mathrm{CMA}}.$ $\Lambda_{\rm CFT}^{}$, the dark sector is a CFT, coupled to SM via corresponds to the original operator of the gauge theory. The matching for the example of a state of \overline{L} C GAIN SCOLOI 13 A OI 1, *d*EM \overline{T} *^O*SM ¯ ⇤CFT ! $\frac{1}{2}$ $\left(\frac{\Lambda_{\rm C}}{2}\right)$ $\frac{1}{2}$ σ ^dSM⁻¹ $\frac{\lambda_{\text{CFT}}}{\Lambda D - 4} \, \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{CFT}} \qquad \qquad \lambda_{\text{CFT}} \approx \lambda_{\text{BZ}} \left(\frac{\Lambda_{\text{CFT}}}{M_{\text{DZ}}} \right)^{a_{\text{SM}} - 1} \qquad \qquad D = d + d_{\text{SM}} \, .$ die bilinear operator is, below $\mathbf{I} \cup \mathbf{C} \mathbf{F}^r$ $\lambda_{\text{CFT}} \approx \lambda_{\text{BZ}} \left(\frac{\Lambda_{\text{CFT}}}{M_{\text{DZ}}} \right)$ $M_{\rm BZ}$ $\sqrt{d_{\rm SM}-1}$ ark sector is a CFT, coupled to SM via $\bigwedge \Lambda$ $\bigwedge d_{\text{SM}}-1$ $D = d + d_{\rm SM}$
- "Natural" parameters: $\lambda_{\rm BZ} \sim \mathcal{O}(1)$ $\blacktriangleright \lambda_{\rm CFT} \ll 1$ itural" parameters: $\lambda_{\rm BZ} \sim {\cal O}(1)$ and $\lambda_{\rm CFT} \ll 1$ M_{min} ≈ 1 $i. 1$ utturalness positum ottorion $\sqrt{D}Z = O(1)$
- CFT is generically strongly coupled, so d is a continuous (non-integer) parameter ($d > 1$ from unitarity) Ungry UUUpiuu, UU W TU U UUMINUUUU (MUMINIUUYU)
From Hinitarity) resulting dark matter relic density for the six portal operators in Table 1. We find that $l \geq 1$ from y col *M*
M
M
*M e*d, so *u* is a cont
/) **NUOUS** *O*SM*O*CFT) CFT ⇡ BZ \overline{I} be a subtractionally supposed with the filter term in the filter μ is a continuous (interaction). \bullet CET in annoviaally otropaly coupled point in a continue be *SU*(*N*) and also we do not require the fixed point to be weakly interacting. t and work to lead the interaction of the interaction of the interaction strength. Since the dark sector does not carry SM gauge charges, *O*SM must be gauge-invariant,

Conformal Dark Sector illy illial Dain Jector in the conformal phase. **O** Conformal Dark Sector the e↵ective dimension with more suppression by inverse powers of *M*gap, rendering them operator. Generically the CFT is strongly coupled, and *d* need not be integer. Further, we **DESERVATION IS CHARGED UNDER A GLOBAL SYSTEM**

 $\mathcal{O}_{\mathrm{SM}}\bar{\Psi}\Psi$

fermion bilinear operator is,

$$
S: \ \lambda_{\mathrm{BZ}} \sim \mathcal{O}(1) \longrightarrow \lambda_{\mathrm{CFT}} \ll 1
$$

• Generically, bound states form below this scale. Cosmologically, bound states behave as particles. If one or more are stable, can be DM. e Conoriaally bound states ferm bolew this seale. Cosmologically bound states behave as particles. If one or more are stable, can be DM. UV-divergent, and the NDA estimates of their contributions are proportional to powers of 0. 2010 DUNNO GO particios. Il 0110 01 111010 • Generically, bound states form below this scale. Cosmologically, bound states behave as particles. If one or more are stable, can be DM.

$$
\mathcal{L} = c \mathcal{O}_{\text{CFT}} \qquad c = \frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{D-4}} \langle \mathcal{O}_{\text{SM}} \rangle.
$$

CFT Breaking: Higgs Portal provides predictions for current dark matter relic density which can be compared with the **ing: Higgs Portal** 2.2 CFT Breaking in the Infrared Infrared in the Infrared Infrared in the Infrared Infrared in the Infrared Infrared Infrared in the Infrared Since the Dark Sector CFT contains a relevant operator *O*CFT , the generic expectation is breaking of the CFT is entirely due to its interaction with the SM, Eq. (2.1). For each portal $\mathcal{L} = \mathcal{L}$ **There are sexted are sexted as several distinct contributions to Portrait contributions to be SMGap**, with the N each of them summarized in Table 1. Below, we will discuss each of these contributions. • First-Generation Only: *ⁱ* = 1 for the first-generation quarks or electrons, and 0 for the

- For example, consider the "Higgs portal" coupling: $\mathcal{O}_{\text{\tiny SM}} = H^\dagger H$ • For example, consider the "Higgs portal" coupling: $\hat{O} = H^\dagger H$ form (2.4), with a coecient
	- Below the weak scale: $\mathcal{L} = c \mathcal{O}$
- If \mathcal{O}_{CFT} is relevant (d<4), this perturbation grows in the IR, eventually breaking conformal symmetry. is perturbation grows in the IR, eventually
I $\mathbf y$ interaction term can be replaced with its VEV and dark energy density will be produced with its VEV and dark energy density will be produced with its VEV and dark energy density will be produced with $\mathbf y$ • If \mathcal{O}_{CFT} is relevant (d<4), this perturbation grows in the IR, eventually \bullet If \mathcal{O}_{CFT} is relevant (d<4), this perturbation
	- If no other sources of conformal breaking, the CFT breaking "gap" scale is *^M*gap ⇠ *^c*1*/*(4*d*) *.* (2.5) t sources of conformal preaking, the If no other sources of conformal breaking, the C

$$
M_{\text{gap}} = \left(\frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{d-2}} v^2\right)^{\frac{1}{4-d}}
$$

CFT Breaking: Other Portals

h

[Spin-1 portal: Chiu, Hong, LT Wang, '22] [Spin-1/2 portal: MP, Hong, Youn, '24]

- Below the gap scale, dark sector has particle-like excitations. To be specific, we assume the following (partly QCD-inspired) features: at *M*gap. In this case, *m*DM ⌧ *M*gap is natural, with the DM mass dictated by the amount of ow the gap scale, dark sector has particle-like excitations. To be
the self-interaction bound is bounded from below by the self-interaction below by the self-interaction by the selfecific, we assume the following (partly QCD-inspired) features: ward warm dark matter construction. Ile, dark sector has particle-like excitations. To be isume the following (partly QCD-inspired) features:
- Lightest hadron is a pseudo-scalar particle, "dark pion" alar particle. "dark pion" n is a pseudo-scalar particle, "dark pion"
- Dark pion is a pNGB, $r = m_{\text{\tiny{DM}}}/M_{\text{gap}}$ is a free (radiatively stable) parameter
- Dark pion is stable, plays the role of DM (no anomaly w.r.t. SM) $\frac{1}{2}$ of $\sum_{n=1}^{\infty}$ is a constraint of $\frac{1}{2}$. $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ states with s θ , plays the role of DM (no anomaly w.r.t. SM)
- Scalar or vector "dark rho" with mass $~\sim M_{\rm gap}$ masses ⇠ *M*gap. These states will couple to and mediate both DM self-interactions and its If dark rind with mass $\sim w_{\text{gap}}$
- Rho-pion interactions from symmetry: e.g.

Hadronic Phase EFT \blacksquare c Phase FFT the role of dark matter, see *e.g.* [14, 15].) will be discussed in Section 4. Notably, both the PGB property and a **Z**² global symmetry are in factor in the pions in the pions in the world-be stabilized for pions in the world-be stabilized for pions i anomalous leading to the state of models with dark pion playing with dark pion playing the state of models with dark pion playing the state of models with data control of models with data control of models with data contro

 $\sum_{i=1}^n \sum_{i=1}^n \frac{1}{i!} \sum_{j=1}^n \frac{1}{j!} \sum_{j=1}$ interactions with the Standard Model. We modell the Standard Model. We modell. We modell $\mathcal{L} \sim g_\star \rho^\mu$ $\sqrt{2}$ $\chi^{\intercal} \partial_{\mu} \chi + {\rm h.c.}$ \setminus

the value of *r* is bounded from above by the self-interaction bound and from below by the

- Recall that SM-CFT coupling is operation is a contract scalar for a contract scalar for a contract scalar factor \overline{C} • Recall that SM-CFT coupli
- Symmetries restrict which states can be created by : the Summetries restrict which states can be created by , suggesting that *^O*CFT / ¹ **but Symmetries restrict which states can be created by** ch sta **IES** C \mathcal{L} is the main contribution of \mathcal{L} and \mathcal{L} is the main contribution to pion elastic scale \mathcal{L} 4.3.3 Lepton Portal netries restrict which states can be created by :

• Dark rho mediates DM-SM interactions: for example for lepton portal **Deapth of the contributions of and interactions for example formal** is a scalar operator with scaling dimension *d*. Once the CFT confines, it is expected to was a shift symmetry of . This is the symmetry of . This is the symmetry of . This is a raising to response the symmetry of \mathcal{L} the e↵ective dimension with more suppression by inverse powers of *M*gap, rendering them f_{adv} the poolictes \bullet Dark rho mediates DM-SM interactions: for example for lepton porta pleteness, we consider both scalar and vector mediator-dominated cases in our phenomeno-Neuls upo readicted *NM CNM* is texted in the way for excession for leaster pertel **Dark filo-mediates Divi-Olymne delectron**

*M*gap Ω 2 , Hadronic Phase F Observations of galactic clusters, such a upper bound on the Bullet contribution of the Bullet contribution on cross-section of elastic scattering of non-relativistic DM particles, SI*/m* . 4500 GeV³

• DM elastic self-scattering is mediated by dark rho exchanges: ↓ DM elastic self-scattering is mediated by dark rho
● **DM elastic self-scattering is mediated** by dark rho *Divi* diadelo don operatoring io middiatod by daint into • DM elastic self-scattering is mediated by dark rho exchanges: vector resonance with mass of order *M*gap. Using the e↵ective theory (2.9), the cross-section For the case of the case of a scalar mediator is determined to be considered to be con lastic self-scattering is mediated by da **WIVI** astic self-scattering is mediated by dark rho exchanges:

*g*2 ?

while contributions from \mathcal{L}_1 and \mathcal{L}_2 and \mathcal{L}_3 are subdominant. This is seen by first noting that \mathcal{L}_2

Hadronic Phase EFT *g*? but theoretically unattractive. This leads us to consider an alternative possibility that *g*? ⇠ 1 but the DM state is not a collection of \blacksquare derivatively-coupled PNGB. Derivatively-coupled PNGB. Derivatively-coupled by exchanges of a scalar or a scala
The scalar or a scalar or Γ *r*6 8⇡*M*² *, r* = *m/M*gap (4.3) rate in the SN is calculated as in the gluon portal (see Appendix B.3) and is given by **VIIIV IIIQUU L** At energy scales between *M*gap and ⇤UV, the Dark Sector is described by a CFT. We assume that the CFT contains an operator *O*CFT with a scaling dimension *d <* 4, *i.e.* a relevant

h α **De** created by **he created by :**

$$
\sigma_{SI} \sim \frac{g_{\star}^4}{8\pi M_{\text{gap}}^2} \sim \frac{r^6}{8\pi M_{\text{gap}}^2}
$$
 (scalar rho), or $\sim \frac{r^2}{8\pi M_{\text{gap}}^2}$ (vector rho)
\n• Recall that SM-CFT coupling is $\mathcal{L}_{int} = \frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{D-4}} \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{CFT}}$

ractions: for example for lepton portal ho mediates DM-SM interactions: for example for lepton portal and illustration of all million allowed values of and its equal potion por text. tho mediates DM-SM interactions: for example for lepton portal the regime where this interaction is small enough to consider this breaking perturbatively,

$$
\mathcal{O}_{\text{CFT}} \longrightarrow \frac{M_{\text{gap}}^{d-1}}{g_{\star}} \phi \qquad \qquad \mathcal{O}_{\text{CFT}} \sim \partial_{\mu} \rho^{\mu} \qquad \qquad \mathcal{O}_{\text{CFT}} \sim (\partial \chi)^2
$$

$$
\mathcal{L}\sim\frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{d}}\left(HL^{\dagger}\ell_{R}\right)\mathcal{O}_{\text{CFT}}\rightarrow\frac{\lambda_{\text{CFT}}~v~M_{\text{gap}}^{d-1}}{\sqrt{2}g_{*}\,\Lambda_{\text{CFT}}^{d}}\left(\bar{e}e\right)\phi+\frac{g_{*}}{M_{\text{gap}}}\phi\left(\partial\chi\right)^{2}
$$

Cosmological History

- Phase transition (conformal plasma -> bound states) in the dark sector at $T_{\rm dark}\sim M_{\rm gap}$
- Assume that 100% of energy in the dark sector before the transition is converted to DM
- If dark sector is in thermal equilibrium with SM before the phase transition, observed DM density requires $m_{\text{dm}} \sim 100 \text{ eV}$ - hot DM!
- Freeze-in scenario: $T_{\rm dark} < T_{\rm SM}$
- As always with freeze-in, assume that dark sector is not reheated after inflation, populated slowly by SM interactions

- Energy transfer from SM to dark sector occurs when dark sector is conformal energy density \sim
	- CFT energy evolves according to **d**
- Dimensional analysis (if $T_{\text{max}} >>$ all mass scales): $\Gamma_F(S)$
	- Solution to Boltzmann equation: transfer rate is given by This scaling occurs when the SM temperature T is well above all T is well above all T above all T energy T energy T above all \bullet Solution to Boltzmann equation: the energy density of the energy density of the dark sector grows as a sector grows as α as α

 $\rho_{\rm CFT}^{\rm } \sim$

• CFT energy evolves according to
$$
\frac{d\rho_{\text{CFT}}}{dt} + 4H\rho_{\text{CFT}} = \Gamma_E(\text{SM} \rightarrow \text{CFT})
$$

Conformal Freeze-In Canformal Eroozo In *d* dan dan da can only change due to work done against the expansion of the universe: \overline{a} Energy transfor from SM to dark sector escure when dark density as a function of the SM temperature *T*. It is instruction of the discussion of $\mathsf{I}\mathsf{I}\mathsf{I}\mathsf{I}\mathsf{I}\mathsf{I}$ transfer rate is given by the Standard Model plasma, for two di↵erent values of *D*. The red curve (*D <* 9*/*2) shows IR-dominant production, while the blue curve (*D >* 9*/*2) shows UV-dominant production.

• Dimensional analysis (if T_{SM} >> all mass scales): $\Gamma_E(\text{SM} \to \text{CFT}) \sim \frac{\lambda_{\text{CFT}}^2}{2(D-4)} T_{SM}^{2D-3}$. density as a function of the SM temperature *T*. $\Gamma_E(\text{SM} \to \text{CFT}) \sim$ λ_c^2 CFT $\Lambda_\mathrm{CFT}^{2(D-4)}$ CFT $T_{\scriptscriptstyle \rm SM}^{2D-3}$ • Dimensional analysis (if $T_{\rm SM}$ >> all mass scales): $\Gamma_E(\rm SM\to CFT) \sim \frac{\Lambda_{\rm CFT}}{\Lambda^2(D-4)}\,T_{\rm SM}^{2D-3}.$ λ^2 disional analysis (if $T_{\rm SM}$ $>>$ all mass scales). The SM \rightarrow CFT) \sim $\frac{{\rm CFT}}{4.2(D-4)}$ $T_{\rm SM}^{\rm ZD}$ $^{-3}$. density can be predicted without knowledge of UV physics and the reheating temperature.

on T_R scales (such as masses) and the mass gap of the dark sector.⁴ This can be easily shown via on T_R • IR-dominated ("true freeze-in") for $D < 9/2$, otherv IR-dominant production, while the blue curve (*D >* 9*/*2) shows UV-dominant production. **predicted and ark matter in density density density density depending to the P**
P
FR-dominated ("true treeze-in") for $D < 9/2$ *otherwis* is weak, due to the low powers in the exponent for *T^R* compared to the dependence on the

and the control of the sector is the control of the sector is the se = *E*(SM ! CFT)*.* (3.5) **K SECLOI OCCUIS V** Pr n dark sect SECIOI 13

$$
\rho_{\text{CFT}} \sim \frac{M_{\text{pl}}}{\Lambda_{\text{CFT}}^{2D-8}} \left[T^4 \left(\frac{T_R^{2D-9} - T^{2D-9}}{2D-9} \right) \right]
$$

• IR-dominated ("true freeze-in") for $D < 9/2$, otherwise (mildly) depends ("true freeze-in") for $D < 9/2$, otherwise (mildly) $\frac{1}{10}$ instead ("true freeze-in") for $D < 0/9$ otherwise (mildly) denends

Conformal Freeze-In

• A more detailed calculation can be performed using Georgi's "unparticle" **n** be p p2 μ *P* and μ *P P* and *P* and ion can he nerformed using Georgi's "unnarticle" process roughly starts around the electroweak scale \sim v and continues time \sim

- approach becomes, **Lint** \overline{C} *n* c actailed calculation can be performed doing acorgi 5 amparticle tion can be perforr [•] A more detail . (a.4) \leq (a.4) \leq (a.4) \leq (a.4)
- For example, in the Higgs portal: ^{*h*} For ay</sub> 4⇤2*d*⁴ ample, in t , in the Higg: $\overline{}$ $\ddot{}$ *p portal:* the energy transfer rate in this process is given by , the energy transfer rate in the energy

(2⇡)32*E^h*

4

⇤2*d*⁴

Conformal Freeze-In: Higgs Portal In the Higgs portal case, as mentioned before, below the critical dimension *d*⇤ = 5*/*2, Cantormal Eroozo-In: Higge Dorts electroweak phase transition, the e↵ective interaction between the dark sector and the SM To energy transferences is equiled through the equilibrium of the computer \sim The CFT energy density at a function of the Standard Model and Model and Model and Model and Model and Model a perature) can be obtained by integrating the Boltzmann equation given in Eq. (3.5). To get a simple estimate, it suces to do this calculation in the relativistic approximation where the

$$
A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}} \frac{\Gamma(d+1/2)}{\Gamma(d-1)\Gamma(2d)}.
$$
\n
$$
f_d = A_d/16\pi^2
$$

$$
n_h \langle \Gamma(h \to \text{CFT}) \ E \rangle = \iint \mathrm{d}\Pi_h \mathrm{d}\Pi_{\text{CFT}} f_h (2\pi)^4 \delta^4(p_h - P) E_h |\mathcal{M}|^2.
$$

$$
= \iint \frac{\mathrm{d}^3 \vec{p}_h}{(2\pi)^3 2E_h} \frac{\mathrm{d}^4 P}{(2\pi)^4} e^{-\beta E_h} (2\pi)^4 \delta^4(p_h - P) A_d (P^2)^{d-2} E_h \frac{v^2}{4} \frac{\lambda_{\text{CFT}}^2}{\Lambda_{\text{CFT}}^{2d-4}}
$$

$$
= \frac{f_d \lambda_{\text{CFT}}^2 v^2 m_h^{2(d-1)} T}{\Lambda_{\text{CFT}}^{2d-4}} K_2(m_h/T).
$$

$$
\frac{1/2)}{\Gamma(2d)}.\qquad f_d = A_d/16\pi^2
$$

In the relativistic approximation (i.e., taking the limit *m^h* ! 0 in the thermal average CFT (*m*² 32⇡2⇤2*d*⁴

Conformal Freeze-In: Higgs Portal where *T^m* is the *SM temperature* at which the *dark sector temperature* (*T*^D) drops to the mass of the dark matter candidate. We also define the CFT energy density at this temperature as ⇢DM(*T*0) = *A m*⁴ n: miggs Porta

- Strong interactions in the CFT thermalize the transferred energy: ⇢CFT ⌘ *A m*⁴ DM, where A represents a model-dependent measure of the number of degrees of freedom of the CFT (times a constant = ⇡2*/*30). Thus, the relic density is given by where *T*⁰ is the current CMB temperature. Additionally, from Eq. (A.10), *T^m* is given by,
	- $A \tau T^4$ $\rho_{\text{CFT}} = A I_I$ $\rho_{\rm C}$
- Freeze-in stops when $\; T_D \sim m_{\rm dm} \,$: • Freeze-in stops when $T_D\sim m_{\rm dm}$: $T^4_m = A\, m_{_{\rm E}}^4$ $\begin{array}{c} 4 \\ \text{DM} \end{array}$ $\lceil \circ \cdot \rceil$ (F) $\qquad \qquad \ldots$ define the CFT energy define the CFT energy density at the CFT $U = U \cdot W \cdot U = U \cdot W \cdot \text{with}$ is the reliable point of data matter from the Higgs p in the term of $2M_* f_d \lambda_{\text{atm}}^2$
	- Current DM energy density: $\mathsf{P}\mathsf{M}\mathsf{P}\mathsf{M}$ energy density: and the relic density of data matter from the $\mathsf{M}\mathsf{M}\mathsf{M}$ \int_{0}^{∞} in the theory. $\rho_{\rm DM}(T_0) = A m_{\rm DM}^4 \frac{g_{*}(T_0)T_0}{\sigma_{\rm DM}^2}$ temperatures are below the QCD scale. *g*⇤(*mh*), denoted as just *g*⇤ below, is approximately urrent DM energy density:

$$
T_m^4 = A\, m_{_\text{DM}}^4 \left[\frac{2 M_* f_d \lambda_{_\text{CFT}}^2\, g_*(T_m)}{3 (g_*(m_h))^{3/2} v} \, \left(\frac{m_h}{\Lambda_{_\text{CFT}}}\right)^{2d-4} \left(\frac{v^3}{m_h^3} - 1\right)\right]^{-1}
$$

$$
\text{error } \text{DIVI energy density:}
$$
\n
$$
\rho_{\rm DM}(T_0) = A \, m_{\rm DM}^4 \frac{g_*(T_0) T_0^3}{g_*(T_m) T_m^3}
$$

 $= A I_{\tilde{D}}, A \sim$ \ldots 10 ✓ *m^h* \sim 1 ◆2*d*⁴ ✓ *v*³ $_{\rm FT} = AT_D^4, A \sim 1 \ldots 10$

$$
\frac{\Omega_{\text{DM}}h^2}{0.1} = \left[\frac{m_{\text{DM}}}{1 \text{ MeV}}\right] \left[\frac{\left(A \, f_d^3 \, g_*^{-9/2}\right)^{1/4}}{10^{-5}}\right] \left[\frac{\left(\frac{M_{\text{gap}}}{m_h}\right)^{(6-\frac{3d}{2})}}{10^{-12}}\right]
$$

Conformal Freeze-In: Higgs Portal

scalar rho dominant vector rho dominant

Results: Higgs Portal α S Portal: $\mathcal{O}_{\text{\tiny SM}} = H^\dagger H$

Figure 5: Scalar rho dominant relic density control density control density constraints and observational constraints, $\frac{1}{2}$

• Effective Lagrangian relevant for SN core: $t_{\rm max}$ regime. Again, the c ϵ regime. Again, the dominant production mechanism for dark production mechanism for dark ϵ s Eliective Lagrangian ielevant for Six cole. vant for SN core: **Integration out the SN core:** \blacksquare

> • Trapping: Use hadronic EFT to evaluate DM mean free path in the SN core • Trapt ^e↵(*m^N T*)*^d* Use hadronic EFT ² h: in the state of the stat eva

Supernova Bounds For Higgs portal, the COFI dark matter candidate has mass of order MeV, and can only be *L* ⇠ produced in supernovae. Comparing *M*gap in the Higgs portal model to *T*SN, we learn that CFT *v* ^p2⇤*d*² **h** *OCF* 12⇡*v*

EFT to evaluate DM mean free path in the SN core is unconstrained by stellar cooling considerations.

$$
\mu\nu G^{\mu\nu a} \qquad \mathcal{L} \sim C_G^{(N)} \left(\frac{\alpha_s}{6\sqrt{2}\pi} \right) \left(\frac{M_{\text{gap}}^{4-d}}{v^2 m_h^2} \right) \bar{N} N \mathcal{O}_{\text{CFT}}
$$

$$
\mathcal{L} \sim \frac{\lambda_{\text{CFT}} v}{\sqrt{2} \Lambda_{\text{CFT}}^{d-2}} h \mathcal{O}_{\text{CFT}} + \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^a G^{\mu\nu a} \longrightarrow \mathcal{L} \sim C_G^{(N)} \left(\frac{\alpha_s}{6\sqrt{2}\pi}\right) \left(\frac{M_{\text{gap}}^{4-d}}{v^2 m_h^2}\right) \bar{N} N \mathcal{O}_{\text{CFT}}
$$

 \mathbf{I}

• Production: Use Georgi's trick to evaluate inclusive production rate if $\;T_{\rm SN} > M_{\rm gal}$ or use hadronic CFT to compute DM pair-production in nucleon collisions if ve produc $\frac{1}{2}$ ›n ra
՝•• $H \sim H \cdot T$ *v*2*m*² $> M_{\text{grav}}$ $\mathcal{O}(\mathbf{T})$

\n- Production: Use Georgi's trick to evaluate inclusive production rate if
$$
T_{\rm s}
$$
 or use hadronic CFT to compute DM pair-production in nucleon collision
\n

MFV couplings and observational complings and observational complings and observations, $\mathsf{F}\mathsf{I}$ **MFV couplings Flavor-diagonal couplings**

Quark Portal \blacksquare α uark Portal $\mathcal{O}_{\scriptscriptstyle \text{SM}} = HQ^\dagger q$

MFV couplings

[scalar rho dominant] F_{scalar} the dominant T_{scalar} whichever happens first. For the lepton portal, it continues until *T* = *m^e* or *T* = *M*gap.

scalar rho dominant

[MFV couplings]

Figure 3: A: Dark matter relic density contours (red) and observations (red) and observations (red) and observations (red) and observations (red) constraints (red) and observations (red) constraints, and observations (red and a seal of the dominant at low temperature for the dominant seal of the seal of order the weak of order the weak of the wea

Lepton Portal $\mathcal{O}_{\text{SM}} = H L^{\dagger} \ell_R$

Gluon Portal

scalar rho dominant vector rho dominant

3.4 Gluon Portal: *O*SM $= G^{\mu\nu} G_{\mu\nu}$

The dominant mode of populating the dark sector is through gluon annihilation, *gg* ! CFT.

DM-SM Couplings 4 Dark Matter Phenomenology and Constraints is either that of a "descendant" or multi-trace. This is simply because *O*CFT ⇠ @*µ*⇢*^µ* by **EXAL COLINING** the e↵ective dimension with more suppression by inverse powers of *M*gap, rendering them

 $\overbrace{ }^1 {\rm CFT}$ is a scalar mediator. Right parallise of the SM-CFT $\,$ $\,$ Fxample: MFV I epton Portallise strength of the SM-CFT $\,$ **[Example: MFV Lepton Portal]**

 \overline{c} $\Lambda = (\lambda_{\text{CFT}}^-)$ $-\frac{1}{D}$ $\frac{1}{D-4}$ *·* $\Lambda_{\textrm{CFT}} \sim 10^{10} - 10^{15} \; \textrm{GeV}$ $\Lambda = (\lambda - \frac{1}{D} A)$ $\Lambda = (10^{10} \text{ m/s})$ $\left(\text{CFT}\right)$ and $\left(\text{CFT}\right)$ and $\left(\text{CFT}\right)$

Observational Signatures?

- detection (common feature of freeze-in models)
- DM mass in the 10 keV-1 MeV range **Figure** free-streaming at scales accessible with future improved large-scale structure data
- CFT->matter phase transition in the dark sector at $T \sim M_{\text{gap}}$
- can be formed
- (unfortunately $\Omega_{GW} \propto (T_{\rm dark}/T_{\rm SM})^8$)

• DM-SM Couplings are too weak for production at colliders, direct/indirect

• No structures smaller than Hubble scale at the time of the phase transition

• Stochastic gravitational wave production if first-order phase transition

Summary

Fermionic ("Neutrino") Portal We will now study the conformal freeze-in production in a model where the coupling • *d* 2: The deformation Eq. (3.2) is marginal or irrelevant, and does not lead onic ("Neutrino") Portal symmetry in the interis a necessary condition to obtain a necessary condition to obtain a DM candidate at the end of the end of the
The end of the freeze-in, which are the end of the freeze-in, which is a new problem of the freeze-in, which i

• Only one relevant spin-1/2 gauge-invariant operator in the SM:

 $\mathcal{L}_\mathcal{O} =$

 $\lambda_{\rm CF}^{\alpha\beta}$

• CFT breaking by this interaction is very week (no VEV, does not mix with ˜ EV, UUCS TIUL TIIIX WILIT

- any operator that gets a VEV) • CFT breaking by this interaction is very week (no VEV, does not mix with view ity bound in this case is *d* 3*/*2. Here ↵*,* are lepton flavor indices, which will \mathcal{L}^{\bullet} CFT. additional relevant is very ween (in view or an interaction is very ween (in view
Yor that dets a VEV)
	- Have to add CFT breaking by hand:
- Gap scale becomes a free parameter O_{F11} mechanism generated by the (*HL*)*O*CFT operator.
- UIVI Candidate. Dann Fion again, Or

• DM Candidate: Dark Pion again, or possibly "Composite Sterile Neutrino" In this setup, the mass gap is given by *M*gap ⇠ *c* idate: Dark Pion again, or possibly "Composite Sterile Neutrino"

$$
\mathcal{L}_{\mathcal{O}} = \frac{\lambda_{\text{CFT}}^{\alpha\beta}}{\Lambda_{\text{CFT}}^{d-3/2}} (HL_\alpha) \mathcal{O}_{\text{CFT}}^\beta
$$

• Have to add CFT breaking by hand:
$$
\mathcal{L} \supset \frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{d-3/2}} (HL) \mathcal{O}_{\text{CFT}} + \tilde{c} \, \tilde{\mathcal{O}}_{\text{CFT}}.
$$

CFT*.* (3.4)

$$
\overline{\lambda}\equiv\lambda_{\text{CFT}}\left(\frac{M_{\text{gap}}}{\Lambda_{\text{CFT}}}\right)^{d-3/2}\hspace{10mm}\textbf{Sample Point:}\hspace{0.3cm}m_{\chi}=10\,\, \overline{\hspace{-1.2cm}1}.
$$

◆*^d*3*/*² plotted against the DM mass *m*, while in the right panel, it is plotted against the

z 10 keV, M_{gap} Ω reproduced the representative the representative that Ω observed relic density w.r.t the DM mass *m* (left) and dimension *d* (right), for Λ $\overline{25.51012 \text{ CaV}}$ observed relic density w.r.t the DM mass *m* (left) and dimension *d* (right), for $\overline{}$ **Sample Point:** $m_{\chi} = 10$ keV, $M_{\text{gap}} = 1$ MeV, $d = 2.4, \, \lambda_{\text{CFT}} = 0.1,$ $\Lambda_{\textrm{CFT}} = 2.5\times 10^{12}\textrm{ GeV}$ $\textbf{Sample Point:} \quad m_\chi = 10 \,\, \mathrm{keV}, \, M_\mathrm{gap} = 1 \,\, \mathrm{MeV}, \, d = 2.4, \, \lambda_\mathrm{CFT} = 0.1,$

Constraints (DP or CSN)

X-Ray Constraints (CSN Only)

• Composite Sterile Neutrino DM can decay:

- X-ray observations constrain the rate of this process such dark matter candidates. Hence, there is no significant bound on our scenario
- Conventional production model for SN DM $\stackrel{\sim}{\sim}$ Dodelson-Widrow mechanism - is ruled out onventional production model for SN in the literature [59, 60]. The dominant production channel for sterile neutrino is ogelson-vvigrow mechanism - is rule
- Composite SN with COFI production can evade this bound evade this bound formposite are with GOL production of reference in sterile neutrino-like DM. For PGB DM, the lightest fermionic composite fermionic compo
- Potential observational signature in future Xray observations \mathcal{A} s already mentioned in Section 3.2, in models where the data is models where the data is \mathcal{A}

- Suppose there is a massless chiral (right-handed) composite fermion • Suppose there is a massless chiral (right-handed) composite fermion *m posite fermion* ⇠ ¹⁰¹³*.* (5.4)
- Then this interaction generates a Dirac "SM" neutrino with mass

$$
m_{\nu}\sim \overline{\lambda}v
$$

• Additional structure in the DS hadronic sector required to avoid annihilation of • Additional structure in the DS hadronic sector required to avoid annihilation of

DM particles into SM neutrinos \sim 8.1110 and 110 a.m. 110 a.m. 110 a.m. 1110 a. • Additional structure in the DS hadronic sector required to avoid annihil DM particles into SM neutrinos $\chi \chi \rightarrow \psi_0 \psi_0$

The CFT operator interpolation Eq. (3.5) and the electroweak symmetry breaking dronic phase, active neutrino couples to a tower of composite

Neutrino Mass Generation utrino Mass Generation left-handed composite partner, is required. Such composite chiral massless fields may arise naturally in theories where they are required by 't Hooft anomaly matching.¹¹ If such a massless composite fermion ⁰ is present, the portal interaction pairs it up

• In the DS hadronic phase, active neutrino couples to a tower of composite "sterile neutrinos": **chiral** specifical speci give rise possible, active medicine coapice to a $\mathsf{rinos}\texttt{''}: \mathsf{rums}$ *m*⌫ ⇠ *v ,* (5.3)

$$
\frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^{d-3/2}} (HL) \mathcal{O}_{\text{CFT}} \sim \lambda_{\text{CFT}} v \sum_{n} a_n \left(\frac{M_{\text{gap}}}{\Lambda_{\text{CFT}}} \right)^{d-3/2} (\nu_L \psi_n) = \sum_{n} a_n \overline{\lambda} v (\nu_L \psi_n),
$$

$$
m_{\nu} \sim \overline{\lambda}v
$$
 need $\overline{\lambda} \sim 10^{-13}$

DM and Neutrino Mass

from the same portal interaction to the measured neutrino mass scale, $\frac{1}{2}$ eV, for several representative values of $\frac{1}{2}$ eV, for several representative values of $\frac{1}{2}$ eV, for several representative values of $\frac{1}{2}$ eV, for several repres

• Correct DM relic density and active neutrino mass scale can be obtained

- AdS/CFT correspondence indicates that the above setup has a 5D dual: AdS slice, SM on UV brane, DM IR-localized
- \bullet $\mathcal{O}_{\rm CFT}^{}$ is dual to a bulk scalar field
- Key feature of COFI: Conformal symmetry breaking in the SM determines the scale of CFT breaking in the IR
- In 5D: Physics on the UV brane sets up the position of the IR brane **.** In 5D: Physics on the UV brane sets up the position of the in prane
 $\frac{1}{2}$ broken at the constant symmetry is broken at the conformal symmetry is broken at the control of t
	- Realized explicitly in "Relevant Dilaton Stabilization" models (constructed for EW/ Planck hierarchy stabilization)

[Csaki, Geller, Heller-Algazi, Ismail, '23]

[work in progress with Lillian Luo]

5D Dual: Relevant Dilaton • First-Generation Only: *ⁱ* = 1 for the first-generation quarks or electrons, and 0 for the

5D Dual: Relevant Dilaton where *y* is the orbifolded fifth dimension. The UV and the IR branes are the two orbifold fixed points at *y* = 0 and *y* = *yc*, respectively. This metric is a solution to the Einstein p*g*ind p*g V*UV()(*y*) *S* = **z** d4*x* d*y* p*g* 1 **V** *M* \overline{M} 2 *m*2² tach tachy is stable. The solution is stable to the solution is stable. The solution is stable. The solution i
The solution is stable. The solution is stable. The solution is stable. The solution is stable. The solution as showar in App. A, the evant biraton is obtained by integrating the distribution is obtained by integrating To complete our construction of the dilaton potential, we mistune the IR and UV tensions. The formulations of the form in the potential give a 4 term in the potential, and the latter will gi p*g*ind p*g V*UV()(*y*) $\overline{}$ p*g V*IR()(*y yc*) $\sum_{i=1}^{n}$

• In relevant dilation model, bulk action is procedure with *S*, integration by parts leaves using the boundary terms in the boundary terms, since it is a single section of \mathbf{v} • In relevant dilation model, bulk action is

• Minimizing the bulk action fixes the location of the IR brane (or equivalently $\overline{}$ *m*Cation of the IR b smaller than the UV scale. For the zero modes of , which are only *y*-dependent, the solutions to the bulk equa- *^L ^R*, with one of the fermions odd under the *Z*² symmetry. A fermion condensate can Be puin action fixes the location of the in biane (or equivalently the bulk action fixes the location of the IR brane (or equivalently

.. ion fixes the location of the IR brane (or equivalently

be generated from the dynamics of some new confining gauge gauge gauge group similar to \mathcal{L} scale of the condensation is controlled by dimensional transmutation and can be naturally \overline{a} $\sum \frac{1}{4}$ $M_{\text{can}} = \left(\begin{array}{c} \text{``CF'} \end{array} \right)$ (*x*) $\frac{1}{2}$ *e*(*x*) $\frac{1}{2}$ *e*(*x*) $\frac{1}{2}$ *e*(*x*) $\frac{1}{2}$ *e*(*x*) $\frac{1}{2}$ $f(\chi) = k \left(\frac{\partial}{\partial \chi} \right)$, where χ are only χ are only χ tions of motion (EOM) are *^e*(2*±*⌫)*ky*, where ⌫ ⌘ ^p4 + *^m*2*/k*2. We assume that 0 *<* ⌫ *<* 2 so $t\omega = \sqrt{4+m^2/k^2}$ and the UV branch solution dominates. The solution of ω in COFI (Higgs portal) $\chi \equiv ke^{-ky_c} \qquad \langle \chi \rangle = k \left(\frac{\lambda_{2\nu}^2}{2\lambda} \right) \qquad \qquad M_{\rm gap} = \left(\frac{\Lambda_{\rm CFT}}{\Lambda_{\rm CFT}} v^2 \right)$ can have any power between 1 and 4 while the size of the size of the size of this coupling is proportional to 2 which is proportional to 2 wh ⇠ *^k*1*/*(2⌫) s condensation of the condensation of λ For the zero modes of , which are only *y*-dependent, the solutions to the bulk equa- \bigwedge_{CFT} $\Lambda_{\scriptscriptstyle\rm CFT}^{d-2}$ CFT v^2 ◆ 1 $4-d$ $\sqrt{4+m^2/k^2}$ in COFI (Higgs portal)

 $\mathcal{P}_{\mathcal{A}}$ 1 + 1*e*2⌫*ky*⌘

•
$$
\chi \equiv ke^{-ky_c}
$$
 $\langle \chi \rangle = k \left(\frac{\lambda_{2\nu} \nu}{2\lambda}\right)^{1/(4-2\nu)}$

$$
S_{\Phi} = \int d^4x dy \sqrt{g} \left[\frac{1}{2} g^{MN} \partial_M \Phi \partial_N \Phi - \frac{1}{2} m^2 \Phi^2 - \frac{\sqrt{g_{\text{ind}}}}{\sqrt{g}} V_{\text{UV}}(\Phi) \delta(y) - \frac{\sqrt{g_{\text{ind}}}}{\sqrt{g}} V_{\text{IR}}(\Phi) \delta(y - y_c) \right]
$$

$$
V_{\text{IR}}(\Phi) = \frac{1}{2} m_{\text{IR}} \Phi^2
$$

$$
V_{\text{IR}}(\Phi) = \frac{1}{2} m_{\text{IR}} \Phi^2
$$

- The UV-brane tadpole term serves as a source for the bulk field where *gind is the determinance* on the induced metric on the induced metric on the branes. <u>The induced metric on</u> metry when tadpole term softly as a • The UV-brane tadpole term serves as a source for the bulk field 48*M*³ and the constitution of the serves as a souled for the buin field
- dilation vev): mizina th 2 **e** bulk action fixes the Ide is dimensionless and can be taken to be very small since it is the only source of *Z*² breaking • Minimizing the bulk a **R**, *R*, *R*, *R*, *L R*, with one of the intervals of the *LD* brane (or or be generated from the dynamics of some new configure group similar to \sim interaction coupling dependence to mass gap dependence as,

$$
\nu \equiv \sqrt{4 + m^2/k^2}
$$
 in COFI (Higgs portal)

$\overline{}$

be dynamics of some taken to the dynamics of the source for the bulk field. The dynamics of $\mathbf r$ scale of the condensate is controlled by dimensional transmutation and can be naturally aupolo tonni ool voo as a source ior the bank fisia irves as a so

5D dual: Phase Transition

- First-order transition completes promptly at $T_{PT} \sim M_{\rm gap}$
- Gravitational wave production is under investigation

Conclusions

- Dark Sector described by a CFT is a natural and generic possibility
- Coupling of DS to SM necessarily breaks Conformal symmetry
- If coupling is via relevant CFT operator, low-energy phase is non-conformal **can** can contain dark matter
- Conformal Freeze-In (COFI): DS is populated from SM when it is in conformal phase, then undergoes a phase transition in which DM particles are created
- Produces viable DM candidate with mass in the 10 keV-100 MeV range
- Very feeble interactions of DM with SM, but large-scale structure signatures are possible
- Neutrino portal can account for DM relic density and active neutrino mass simultaneously
- Dark Sector phase transition/Gravitational wave production can be studied using 5D dual