Dark Matter from a Conformal Dark Sector

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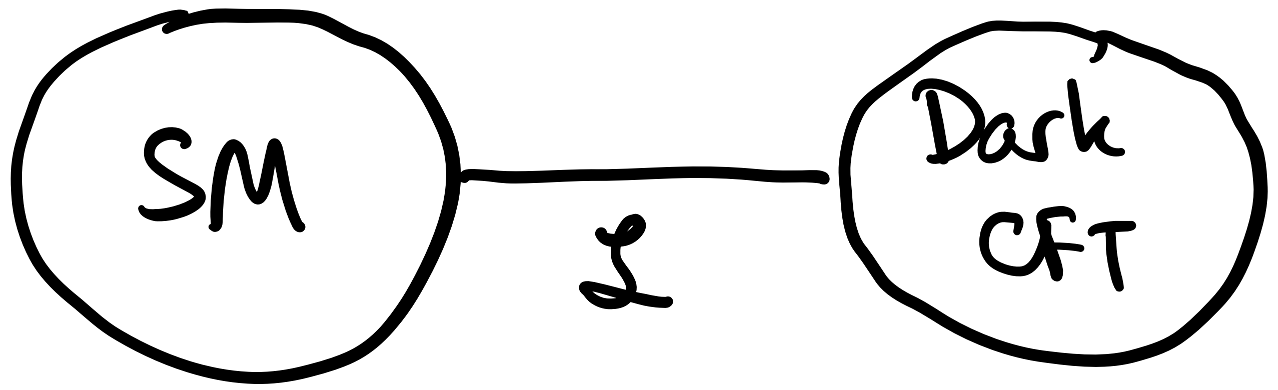
[Work with Sungwoo Hong and Gowri Kurup, 2207.10093, JHEP]

[+work in progress with Lillian Luo]

Conformal(-ish) Dark Sector

- Conformal field theories seem ubiquitous, appear at interacting fixed points of RG flows
- Consider a dark sector described by a CFT (below some UV cutoff >> weak scale)
- Can dark matter arise 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
- This may produce an interesting DM candidate



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

Conformal Dark Sector

- In the deep UV, dark sector is a gauge theory, coupled to SM e.g. via

$$\mathcal{L}_{\rm UV} = \frac{\lambda_{\rm BZ}}{M_{\rm BZ}^{d_{\rm SM}-1}} \mathcal{O}_{\rm SM} \bar{\Psi}\Psi$$

- DS flows to an interacting IR fixed point (Banks-Zaks) at $\Lambda_{\rm CFT} < M_{\rm BZ}$

- Below $\Lambda_{\rm CFT}$, the dark sector is a CFT, coupled to SM via

$$\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \mathcal{O}_{\rm SM} \mathcal{O}_{\rm CFT} \qquad \lambda_{\rm CFT} \approx \lambda_{\rm BZ} \left(\frac{\Lambda_{\rm CFT}}{M_{\rm BZ}}\right)^{d_{\rm SM}-1} \qquad D = d + d_{\rm SM}$$

- "Natural" parameters: $\lambda_{\rm BZ} \sim \mathcal{O}(1)$ ➡ $\lambda_{\rm CFT} \ll 1$

- CFT is generically strongly coupled, so d is a continuous (non-integer) parameter ($d \geq 1$ from unitarity)

CFT Breaking: Higgs Portal

- For example, consider the "Higgs portal" coupling: $\mathcal{O}_{\rm SM} = H^\dagger H$
- Below the weak scale: $\mathcal{L} = c\,\mathcal{O}_{\rm CFT}$ $\qquad c = \frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}}\langle \mathcal{O}_{\rm SM}\rangle.$
- If $\mathcal{O}_{\rm CFT}$ is relevant (d<4), this perturbation grows in the IR, eventually breaking conformal symmetry.
- If no other sources of conformal breaking, the CFT breaking "gap" scale is

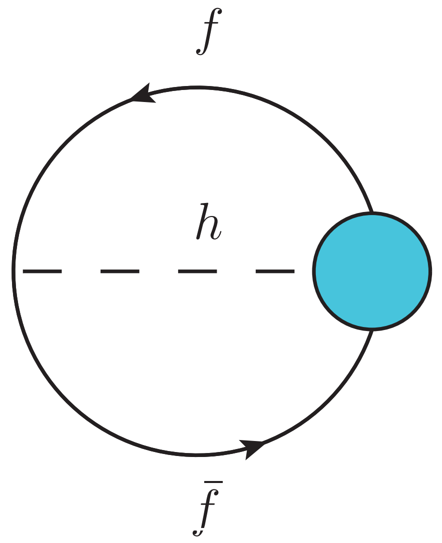
$$M_{\rm gap} = \left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d-2}} v^2\right)^{\frac{1}{4-d}}$$

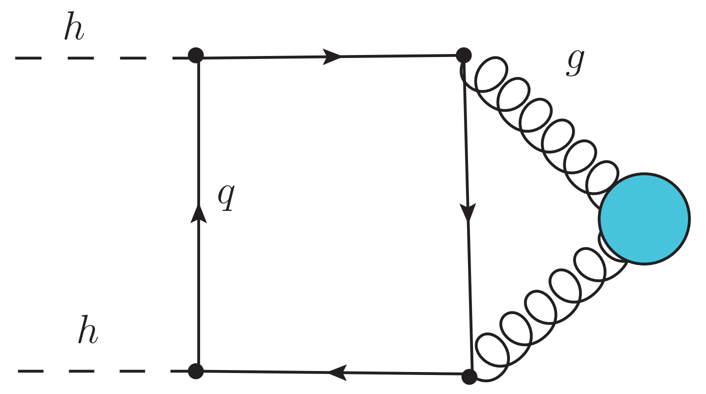
- Generically, bound states form below this scale. Cosmologically, bound states behave as particles. If one or more are stable, can be DM.

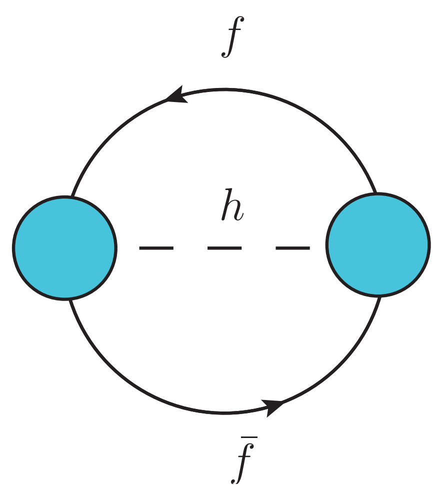
CFT Breaking: Other Portals

	$\mathcal{O}_{\rm SM}$	$\mathcal{O}_{\rm CFT}$ from $\langle \mathcal{O}_{\rm SM} \rangle$	Loop-induced $\mathcal{O}_{\rm CFT}$	Loop-induced $\mathcal{O}_{\rm CFT}$ from $\langle H^\dagger H \rangle$	$\mathcal{O}^2_{\rm CFT}$
Higgs portal	$H^\dagger H$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d-2}} v^2\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d-2}} \frac{\Lambda_{\rm SM}^2}{16\pi^2}\right)^{\frac{1}{4-d}}$	—	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d-2}} \frac{v}{m_h}\right)^{\frac{1}{2-d}}$
Quark portal	$HQ_L^\dagger q_R$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} v \Lambda_{\rm QCD}^3\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{(\sum_i \kappa_i y_{q_i}) v^2 \Lambda_{\rm SM}^2}{(16\pi^2)^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{(\sum_i \kappa_i y_{q_i}) v^2 \Lambda_{\rm SM}^2}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \sqrt{\frac{\Lambda_{\rm SM}^4}{(16\pi^2)^2} + \frac{v^4}{16\pi^2}}\right)^{\frac{1}{2-d}}$
Gluon portal	$G^{\mu\nu}G_{\mu\nu}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \Lambda_{\rm QCD}^4\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^4}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{(\sum_i y_{q_i}^2)\, \alpha_s\, v^2 \Lambda_{\rm SM}^2}{64\pi^3}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^2}{4\pi}\right)^{\frac{1}{2-d}}$
Lepton portal	$HL^\dagger \ell_R$	—	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{(\sum_i \kappa_i y_{\ell_i}) v^2 \Lambda_{\rm SM}^2}{(16\pi^2)^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{(\sum_i \kappa_i y_{\ell_i}) v^2 \Lambda_{\rm SM}^2}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \sqrt{\frac{\Lambda_{\rm SM}^4}{(16\pi^2)^2} + \frac{v^4}{16\pi^2}}\right)^{\frac{1}{2-d}}$
EW portal	$W^{\mu\nu}W_{\mu\nu}$	—	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^4}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{g^2}{4} \frac{v^2 \Lambda_{\rm SM}^2}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^2}{4\pi}\right)^{\frac{1}{2-d}}$
EW portal	$B^{\mu\nu}B_{\mu\nu}$	—	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^4}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{g'^2}{4} \frac{v^2 \Lambda_{\rm SM}^2}{16\pi^2}\right)^{\frac{1}{4-d}}$	$\left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d}} \frac{\Lambda_{\rm SM}^2}{4\pi}\right)^{\frac{1}{2-d}}$

[Spin-1 portal: Chiu, Hong, Wang, '22]







Hadronic Phase EFT

- Below the gap scale, dark sector has particle-like excitations. To be specific, we assume the following (partly QCD-inspired) features:

- Lightest hadron is a pseudo-scalar particle, “dark pion”

- Dark pion is a pNGB, $r = m_{\rm DM}/M_{\rm gap}$ is a free (radiatively stable) parameter

- Dark pion is stable, plays the role of DM (no anomaly w.r.t. SM)

- Scalar or vector “dark rho” with mass $\sim M_{\rm gap}$

- Rho-pion interactions from symmetry: e.g. $\mathcal{L} \sim g_\star \rho^\mu \left(\chi^\dagger \partial_\mu \chi + \text{h.c.}\right)$

Hadronic Phase EFT

- DM elastic self-scattering is mediated by dark rho exchanges:

$$\sigma_{\rm SI} \sim \frac{g_\star^4}{8\pi M_{\rm gap}^2} \sim \frac{r^6}{8\pi M_{\rm gap}^2} \textbf{ (scalar rho), \quad or } \sim \frac{r^2}{8\pi M_{\rm gap}^2} \textbf{ (vector rho)}$$

- Recall that SM-CFT coupling is $\mathcal{L}_{\rm int} = \frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}} \mathcal{O}_{\rm SM} \mathcal{O}_{\rm CFT}$

- Symmetries restrict which states can be created by :

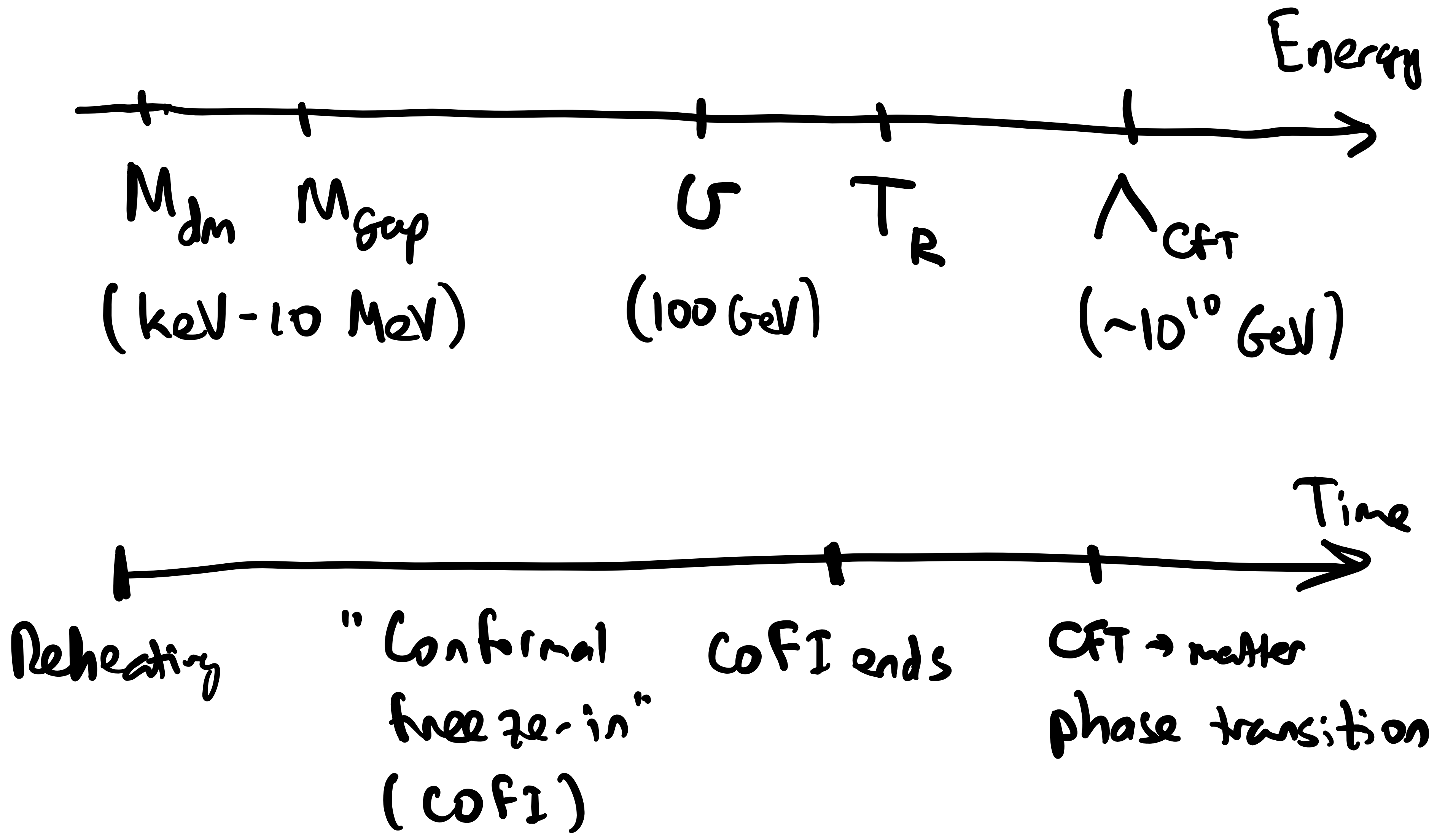
$$\mathcal{O}_{\rm CFT} \longrightarrow \frac{M_{\rm gap}^{d-1}}{g_\star} \phi \qquad \mathcal{O}_{\rm CFT} \sim \partial_\mu \rho^\mu \qquad \mathcal{O}_{\rm CFT} \sim (\partial\chi)^2$$

- Dark rho mediates DM-SM interactions: for example for lepton portal

$$\mathcal{L} \sim \frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^d} \left(H L^\dagger \ell_R \right) \mathcal{O}_{\rm CFT} \to \frac{\lambda_{\rm CFT}\, v\, M_{\rm gap}^{d-1}}{\sqrt{2} g_*\, \Lambda_{\rm CFT}^d} (\bar{e} e)\, \phi + \frac{g_*}{M_{\rm gap}} \phi\, (\partial\chi)^2$$

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 $m_{\rm dm} \sim 100 \text{ eV}$ - 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



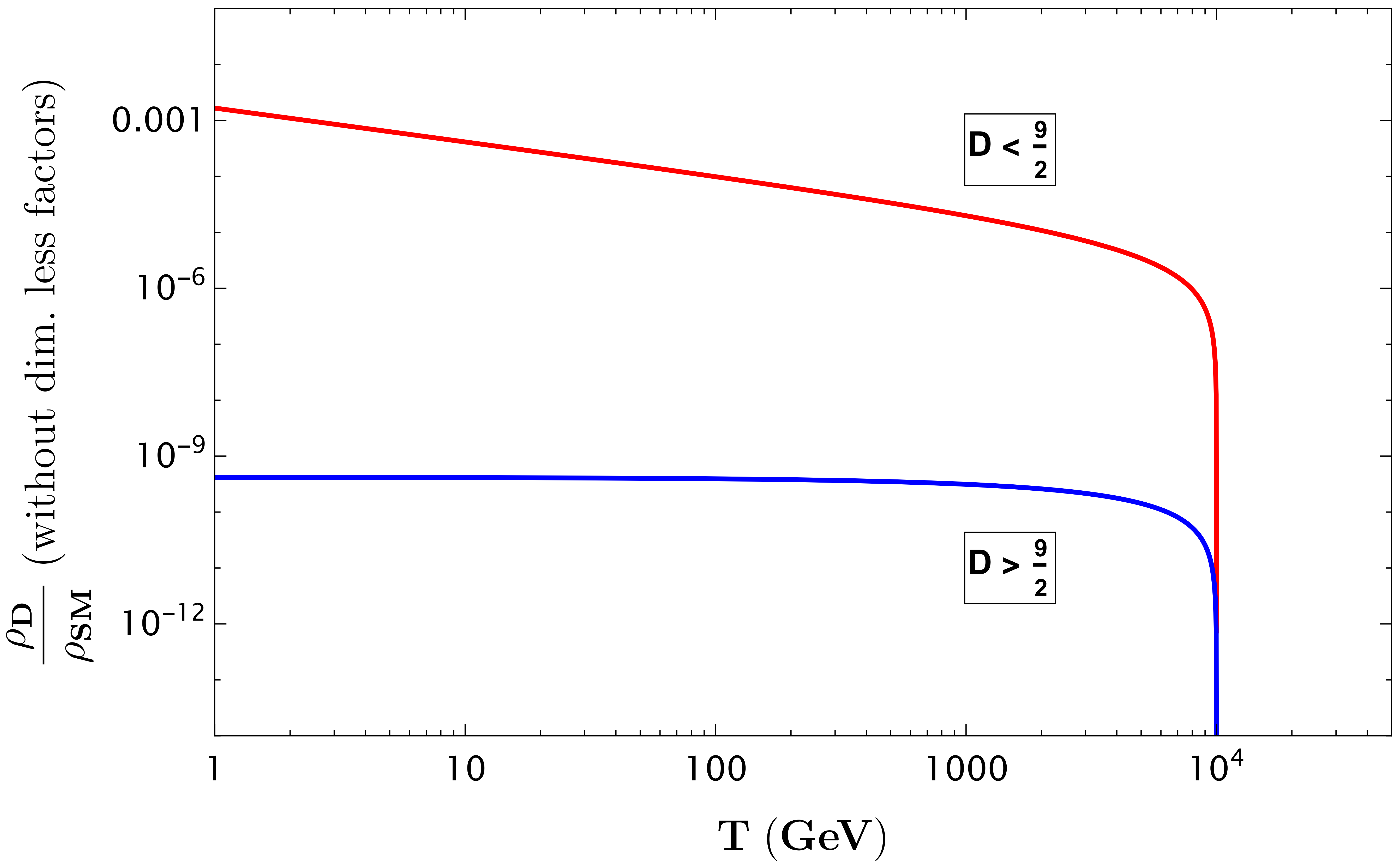
Conformal Freeze-In

- Energy transfer from SM to dark sector occurs when dark sector is conformal
- CFT energy evolves according to $\frac{d\rho_{\rm CFT}}{dt} + 4H\rho_{\rm CFT} = \Gamma_E(\rm SM \to CFT)$
- Dimensional analysis (if $T_{\rm SM}$ >> all mass scales): $\Gamma_E(\rm SM \to CFT) \sim \frac{\lambda^2_{\rm CFT}}{\Lambda^{2(D-4)}_{\rm CFT}} T^{2D-3}_{\rm SM}.$
- Solution to Boltzmann equation:

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

- IR-dominated (“true freeze-in”) for $D < 9/2$, otherwise (mildly) depends on T_R

Conformal Freeze-In



Conformal Freeze-In: Higgs Portal

- A more detailed calculation can be performed using Georgi's "unparticle" approach

- For example, in the Higgs portal:

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

$$= \iint \frac{\mathrm{d}^3\vec{p}_h}{(2\pi)^3 2E_h}\, \underline{\frac{\mathrm{d}^4 P}{(2\pi)^4}}\, \mathrm{e}^{-\beta E_h}\, \underline{(2\pi)^4\; \delta^4(p_h - P)\; A_d\; (P^2)^{d-2}}\; E_h\, \frac{v^2}{4}\, \frac{\lambda^2_{\mathrm{CFT}}}{\Lambda^{2d-4}_{\mathrm{CFT}}}$$

$$= \frac{f_d\, \lambda^2_{\mathrm{CFT}}\, v^2\, m_h^{2(d-1)} T}{\Lambda^{2d-4}_{\mathrm{CFT}}}\, K_2(m_h/T).$$

$\Rightarrow$

$$\rho_{\mathrm{CFT}}(T) = \frac{2M_* f_d \lambda^2_{\mathrm{CFT}}}{3\sqrt{g_*(T)}\, v} \left(\frac{m_h}{\Lambda_{\mathrm{CFT}}}\right)^{2d-4} T^4 \left(\frac{v^3}{T^3} - 1\right)$$

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

$$f_d = A_d/16\pi^2$$

Conformal Freeze-In: Higgs Portal

- Strong interactions in the CFT thermalize the transferred energy:

$$\rho_{\rm CFT} = A T_D^4,\, A \sim 1 \ldots 10$$

- Freeze-in stops when $T_D \sim m_{\rm dm}$:

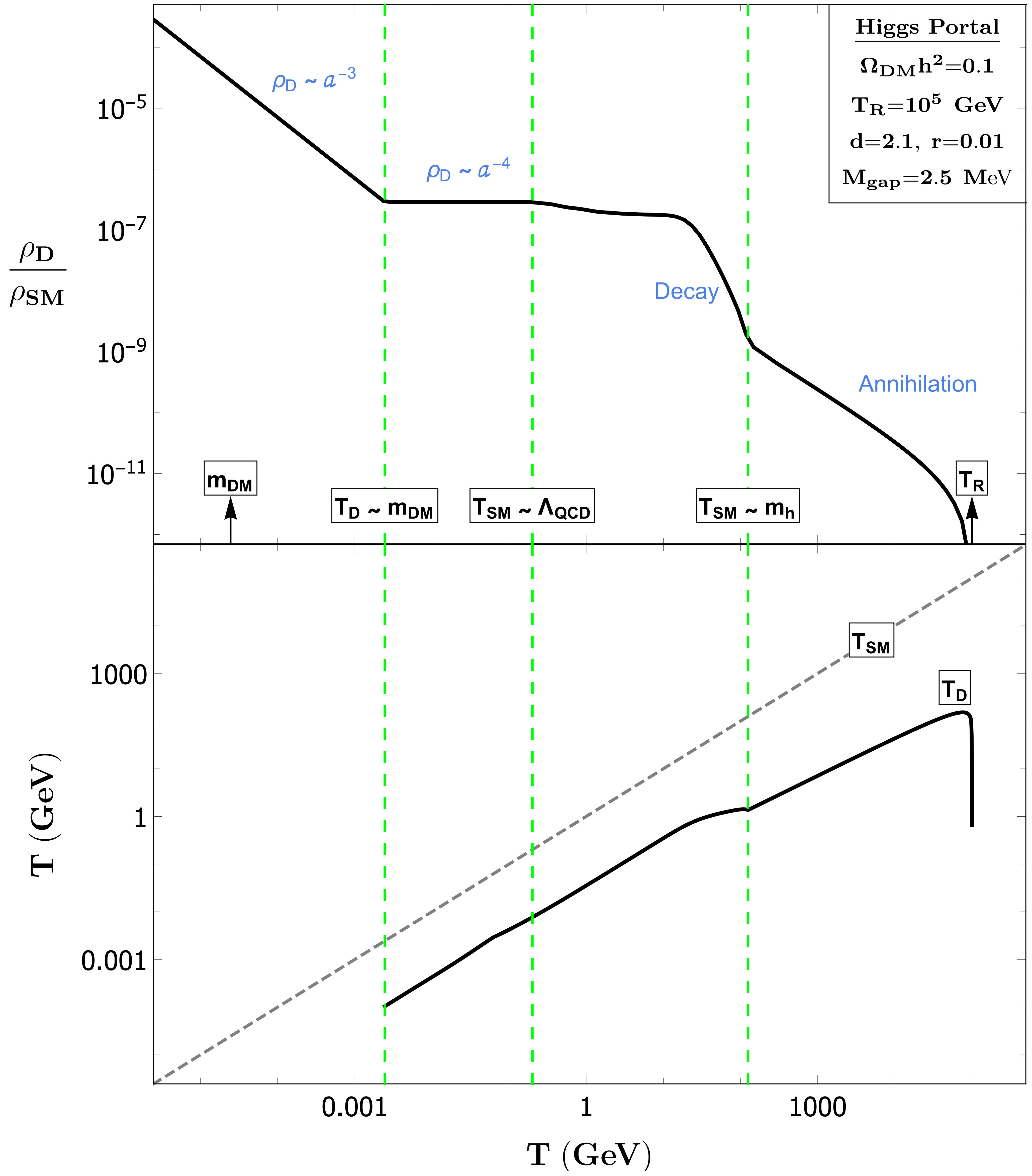
$$T_m^4 = A\, m_{\rm DM}^4 \left[\frac{2 M_* f_d \lambda_{\rm CFT}^2\, g_*(T_m)}{3 (g_*(m_h))^{3/2} v} \left(\frac{m_h}{\Lambda_{\rm CFT}} \right)^{2d-4} \left(\frac{v^3}{m_h^3} - 1 \right) \right]^{-1}$$

- Current DM energy density:

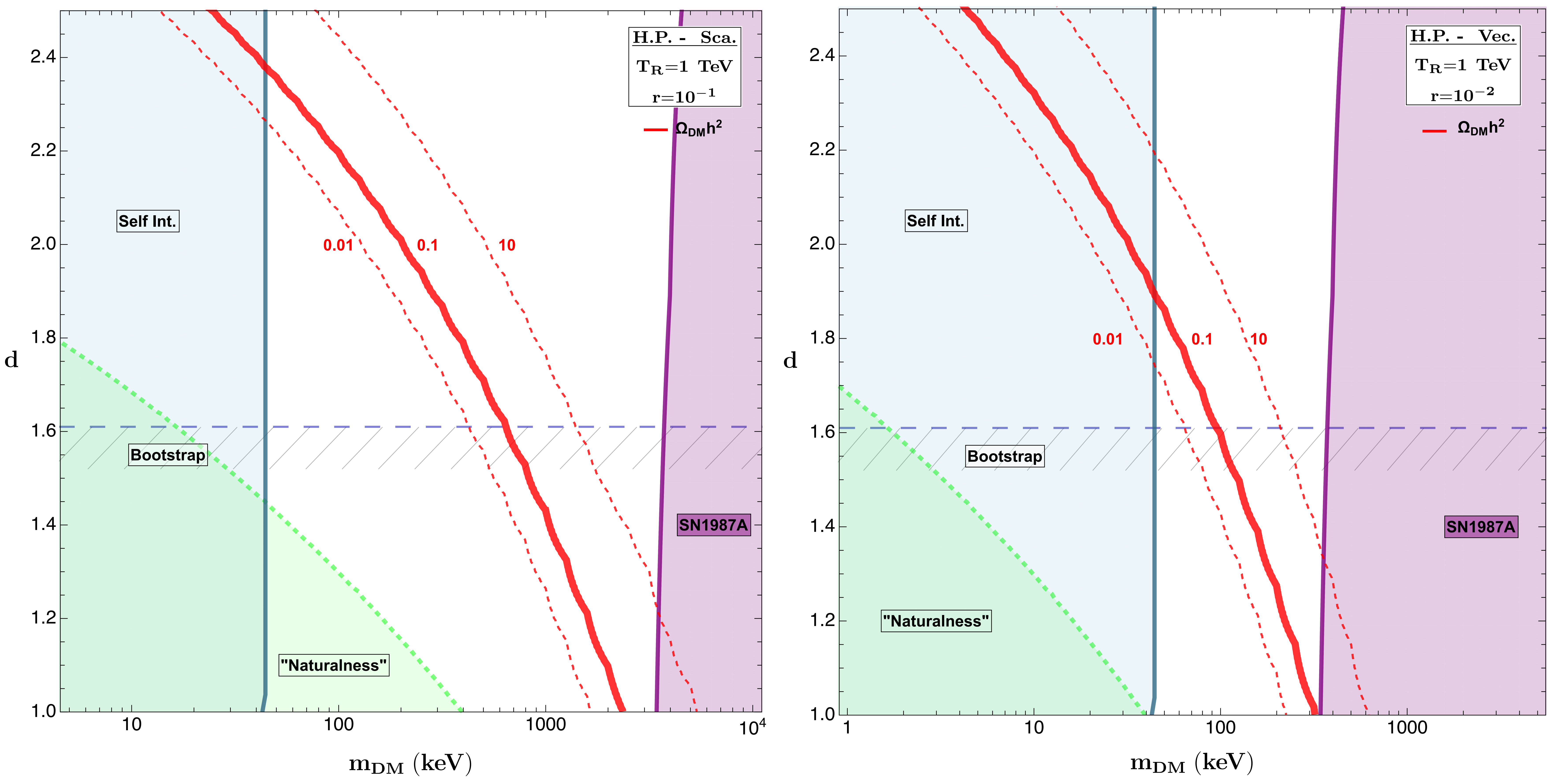
$$\rho_{\rm DM}(T_0) \;=\; A\, m_{\rm DM}^4 \frac{g_*(T_0) T_0^3}{g_*(T_m) T_m^3}$$

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

Conformal Freeze-In: Higgs Portal



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

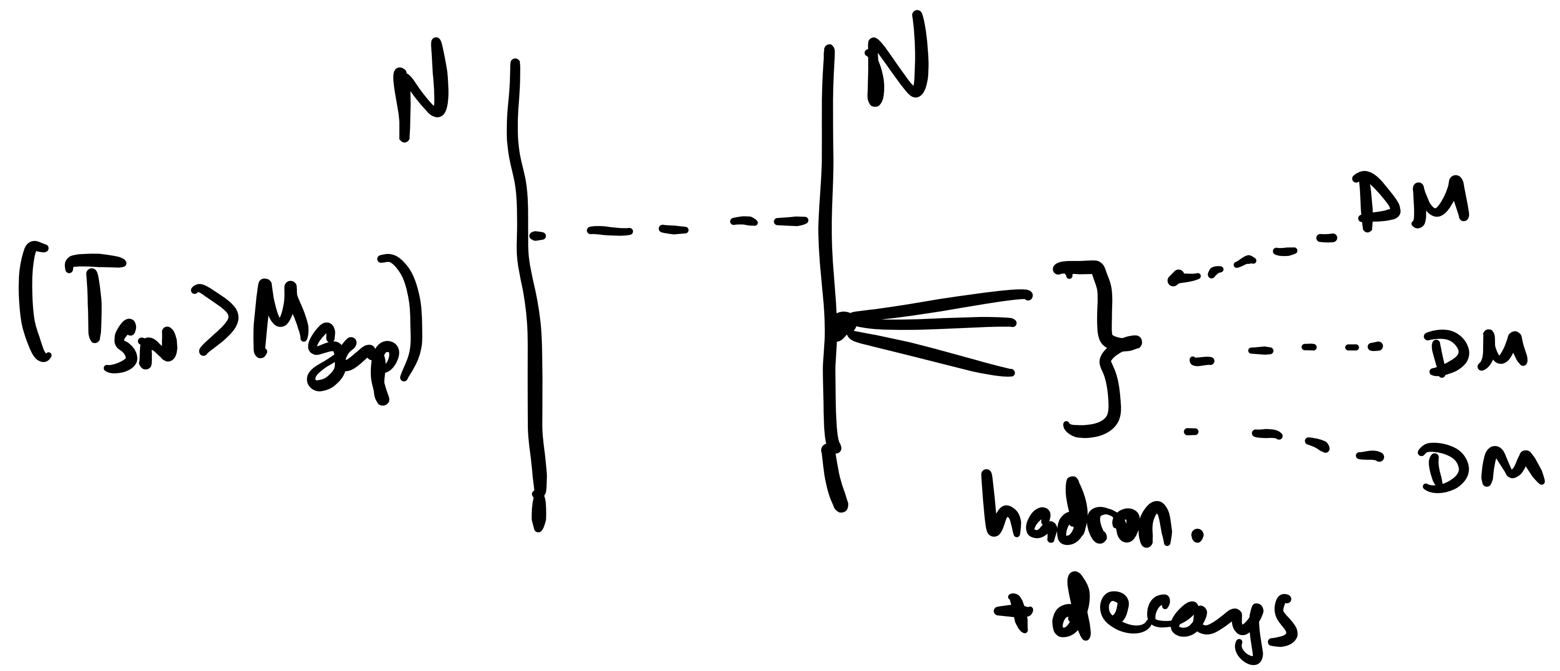


scalar rho dominant **vector rho dominant**

Supernova Bounds

- Effective Lagrangian relevant for SN core:

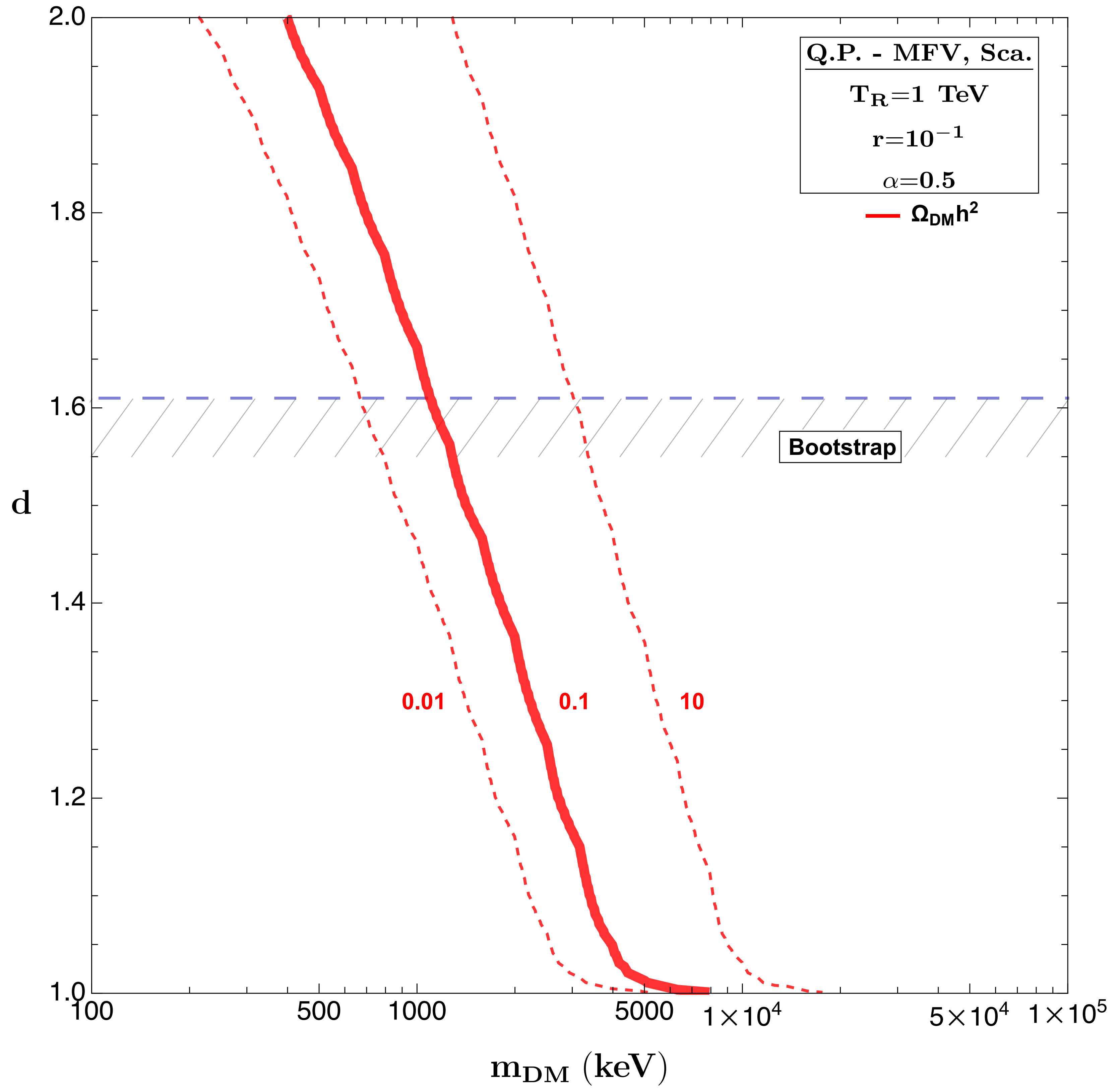
$$\mathcal{L} \sim \frac{\lambda_{\rm CFT}\, v}{\sqrt{2}\Lambda_{\rm CFT}^{d-2}}\, h\, \mathcal{O}_{\rm CFT} + \frac{\alpha_s}{12\pi v}\, h\, G^a_{\mu\nu} G^{\mu\nu a} \quad \longrightarrow \quad \mathcal{L} \sim C_G^{(N)} \left(\frac{\alpha_s}{6\sqrt{2}\pi}\right) \left(\frac{M_{\rm gap}^{4-d}}{v^2\,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



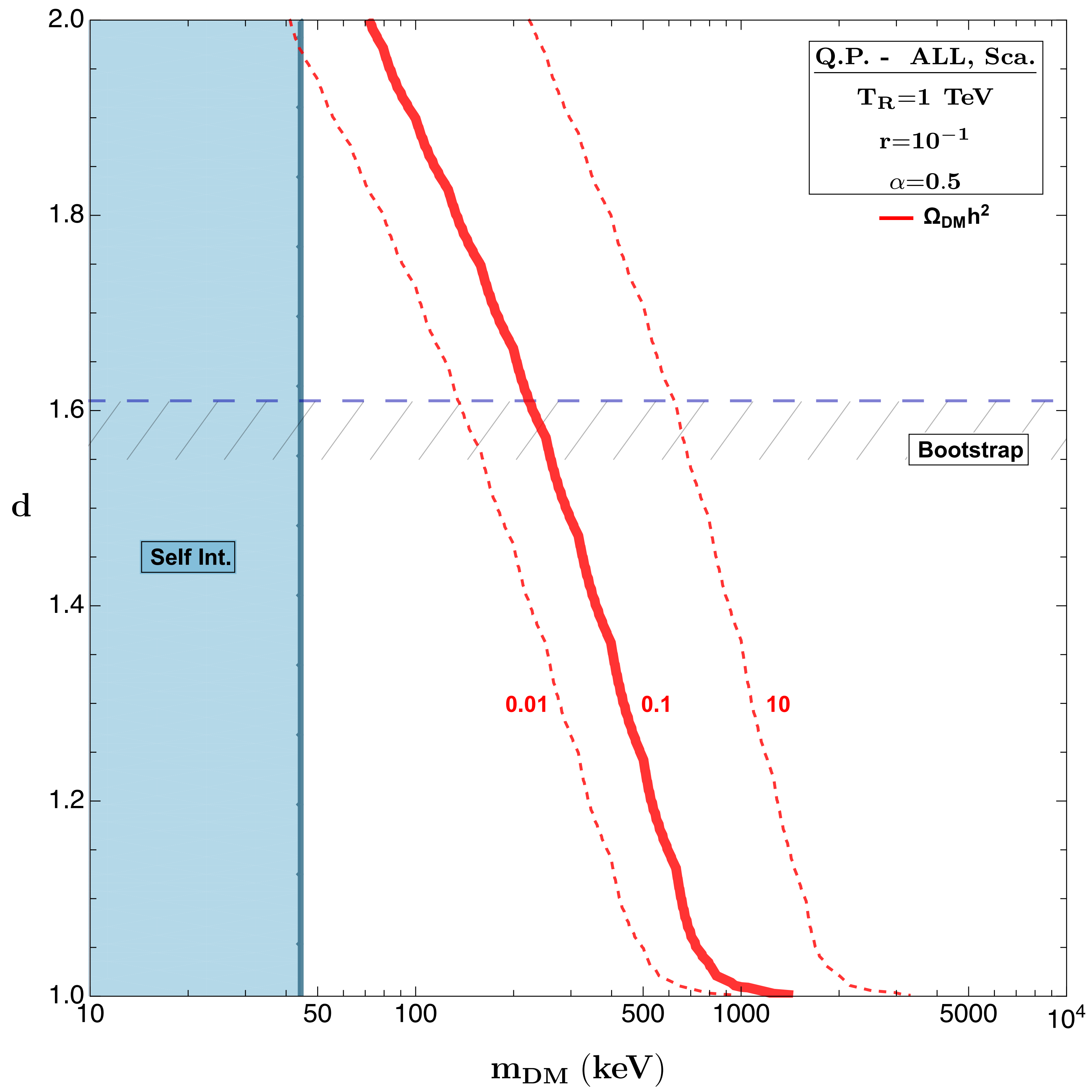
- Production: Use Georgi's trick to evaluate inclusive production rate if $T_{\rm SN} > M_{\rm gap}$ or use hadronic CFT to compute DM pair-production in nucleon collisions if $T_{\rm SN} < M_{\rm gap}$

- Trapping: Use hadronic EFT to evaluate DM mean free path in the SN core

Quark Portal $\mathcal{O}_{\rm SM} = HQ^\dagger q$



MFV couplings

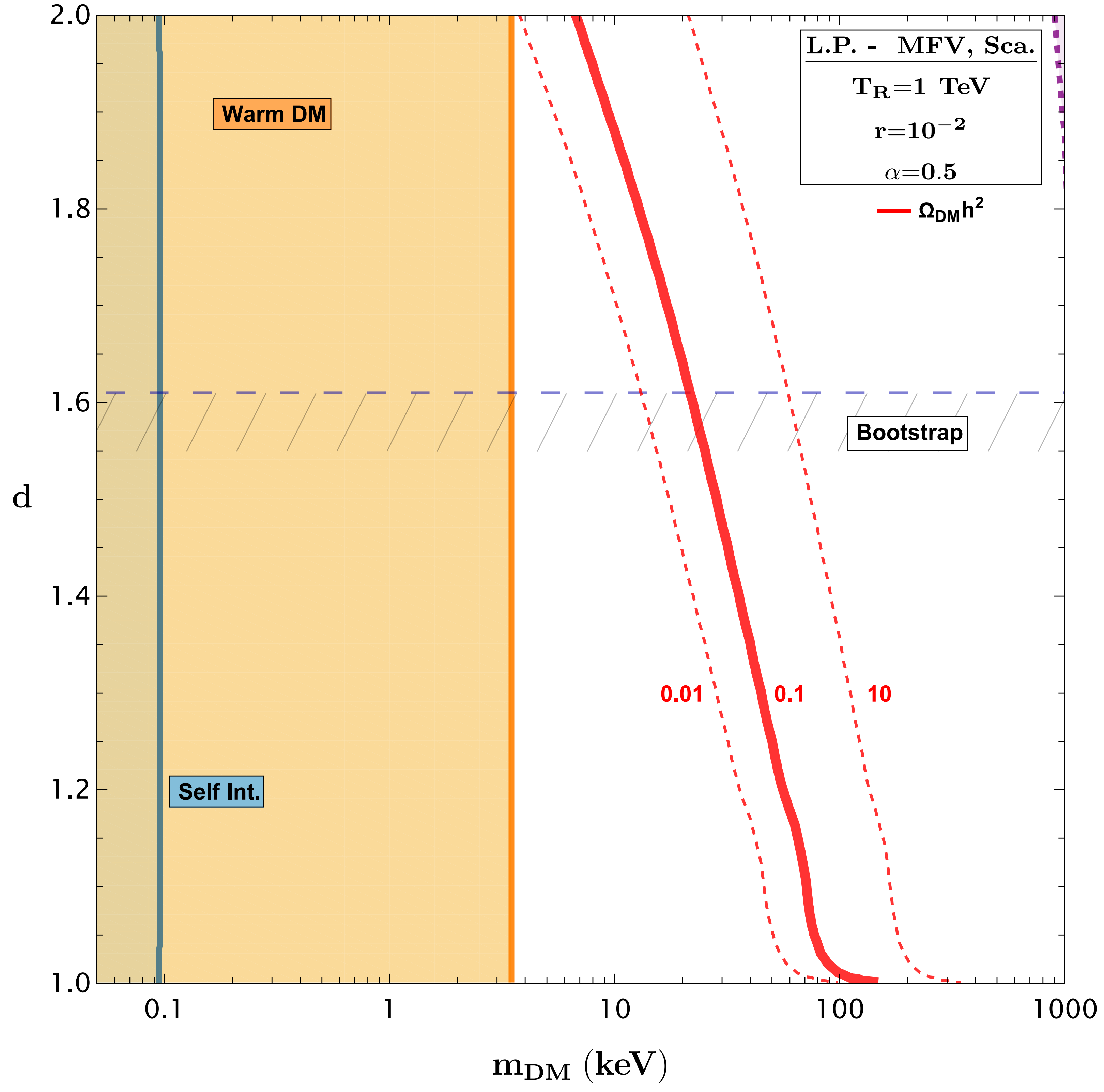


Flavor-diagonal couplings

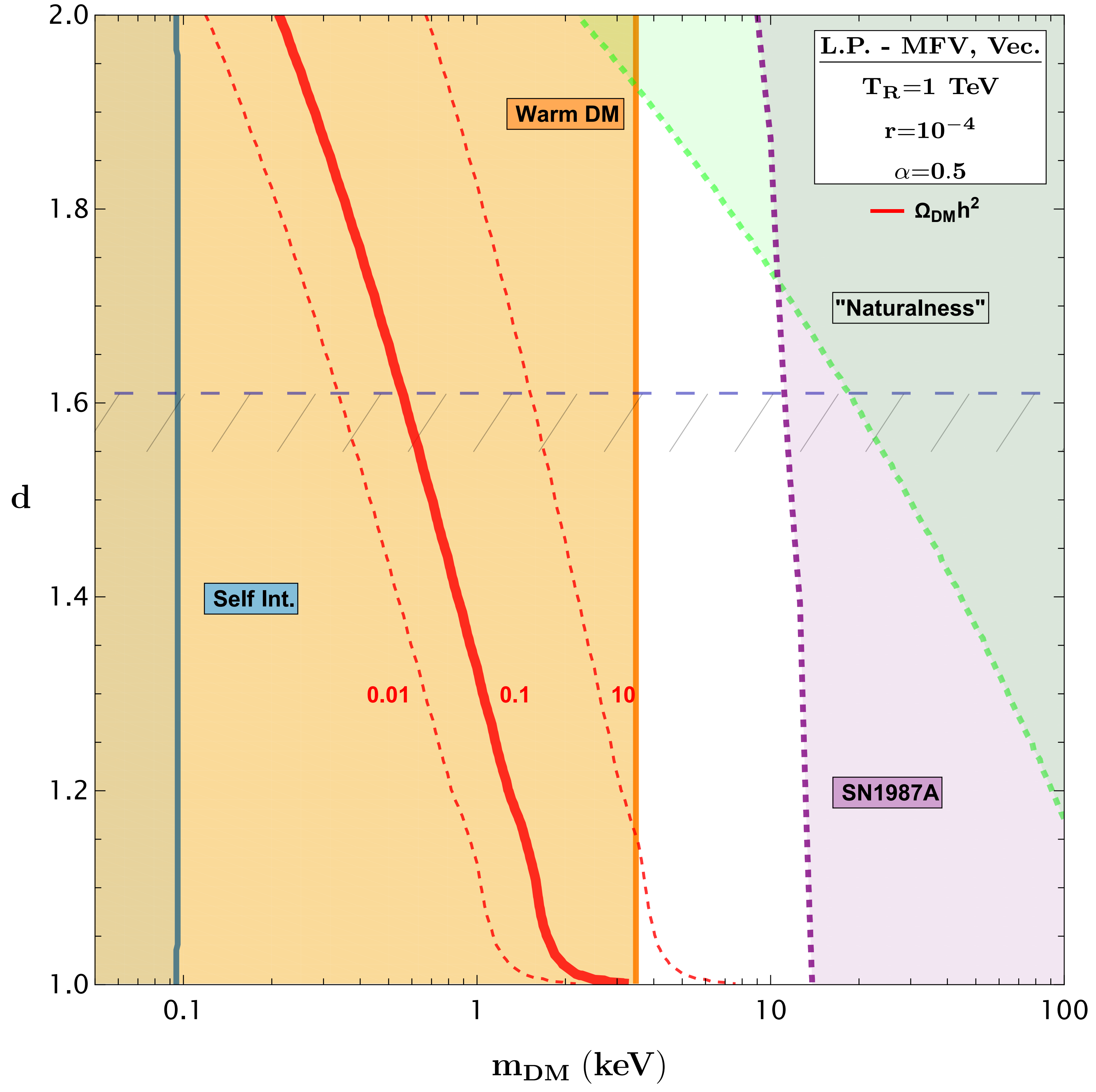
[scalar rho dominant]

Lepton Portal

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



scalar rho dominant

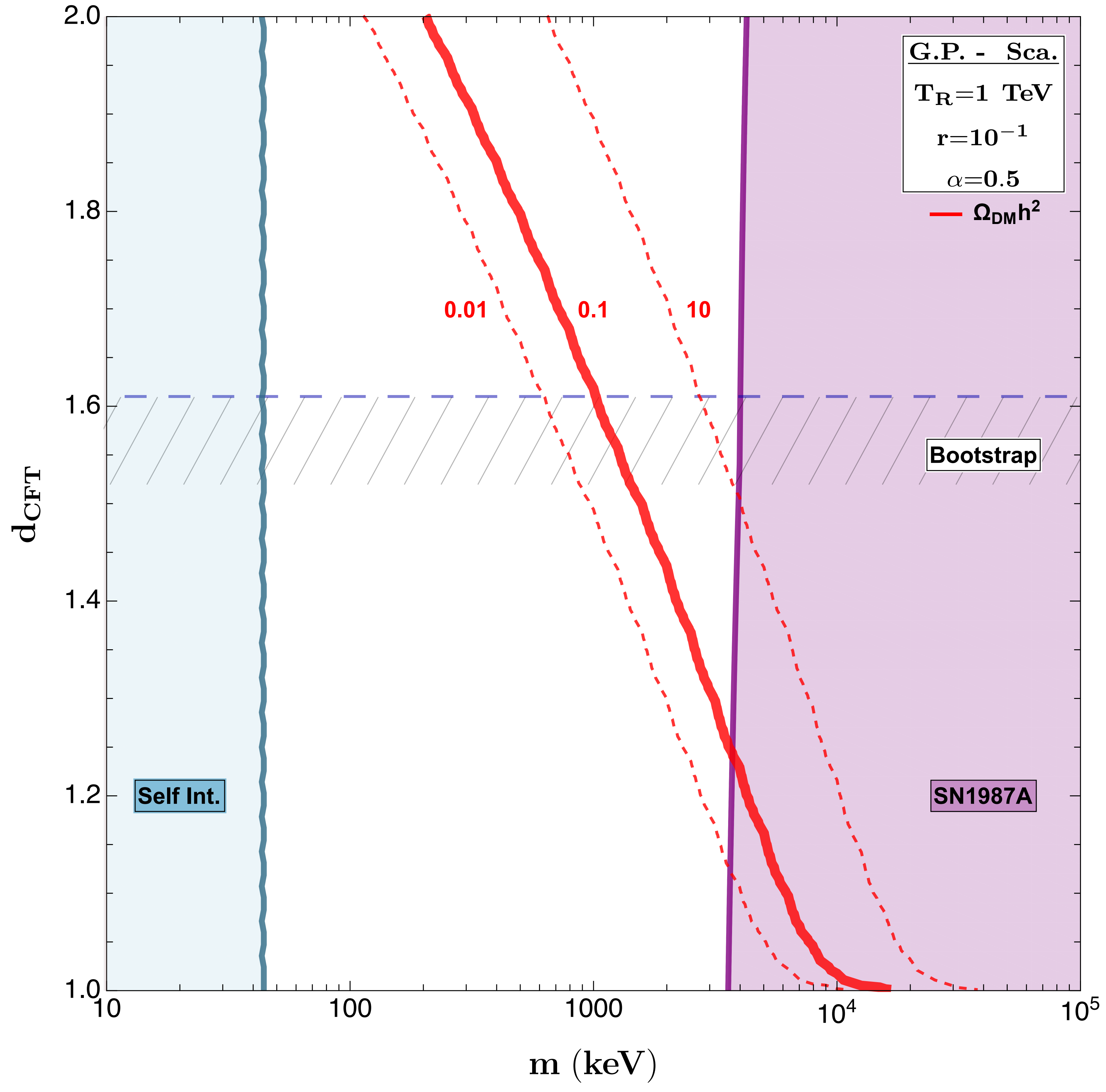


vector rho dominant

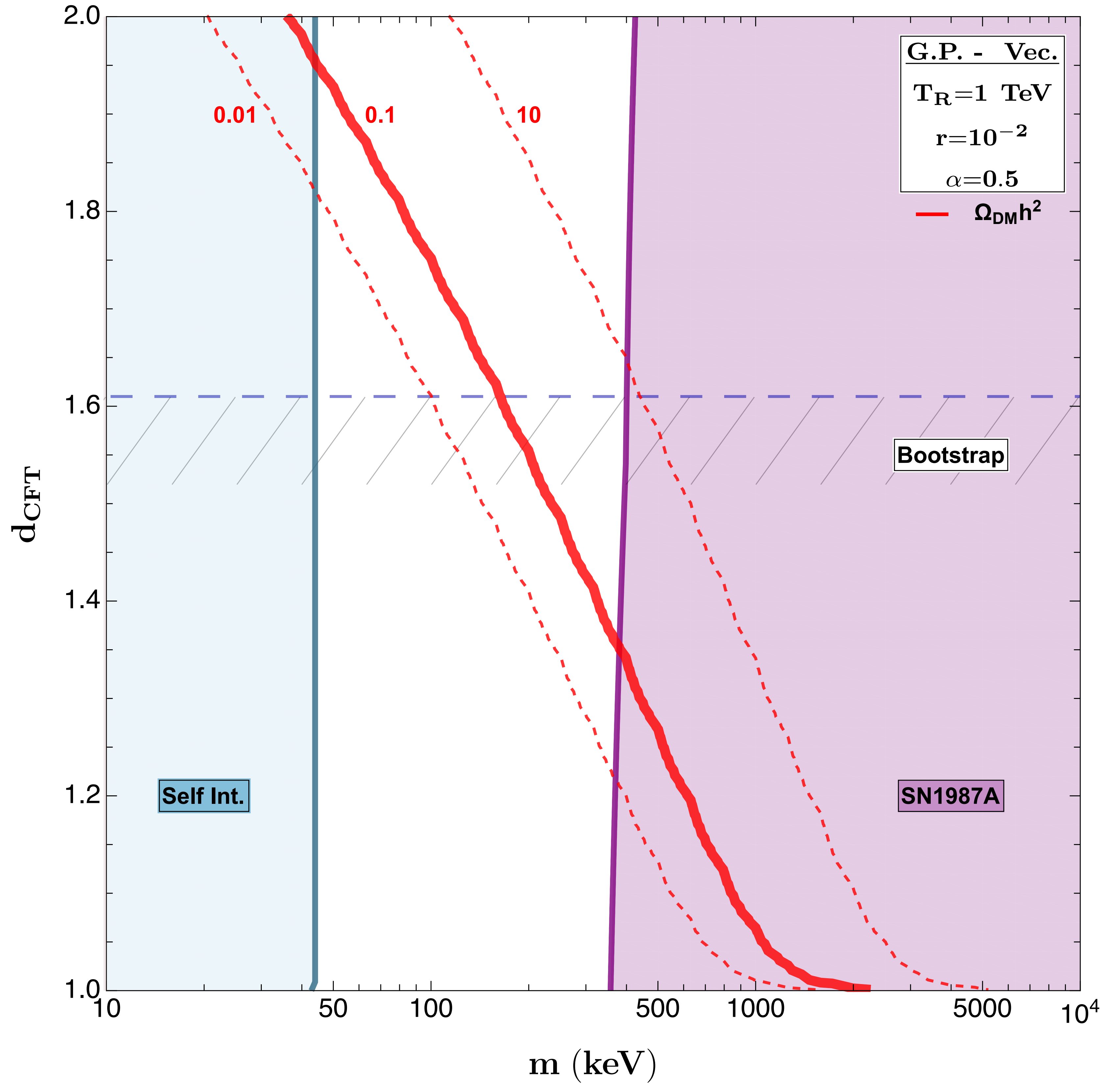
[MFV couplings]

Gluon Portal

$$\mathcal{O}_{\rm SM} = G^{\mu\nu}G_{\mu\nu}$$

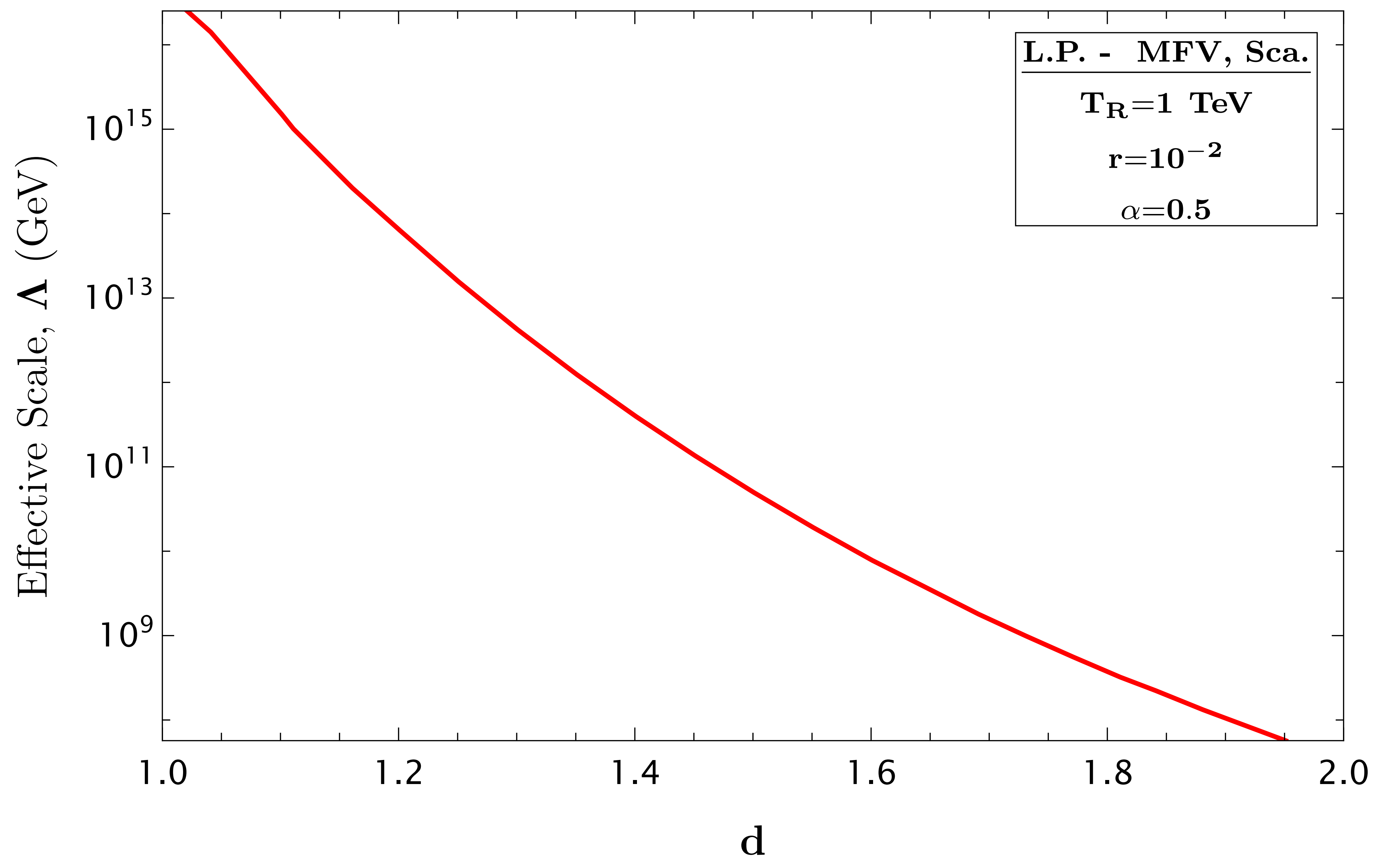


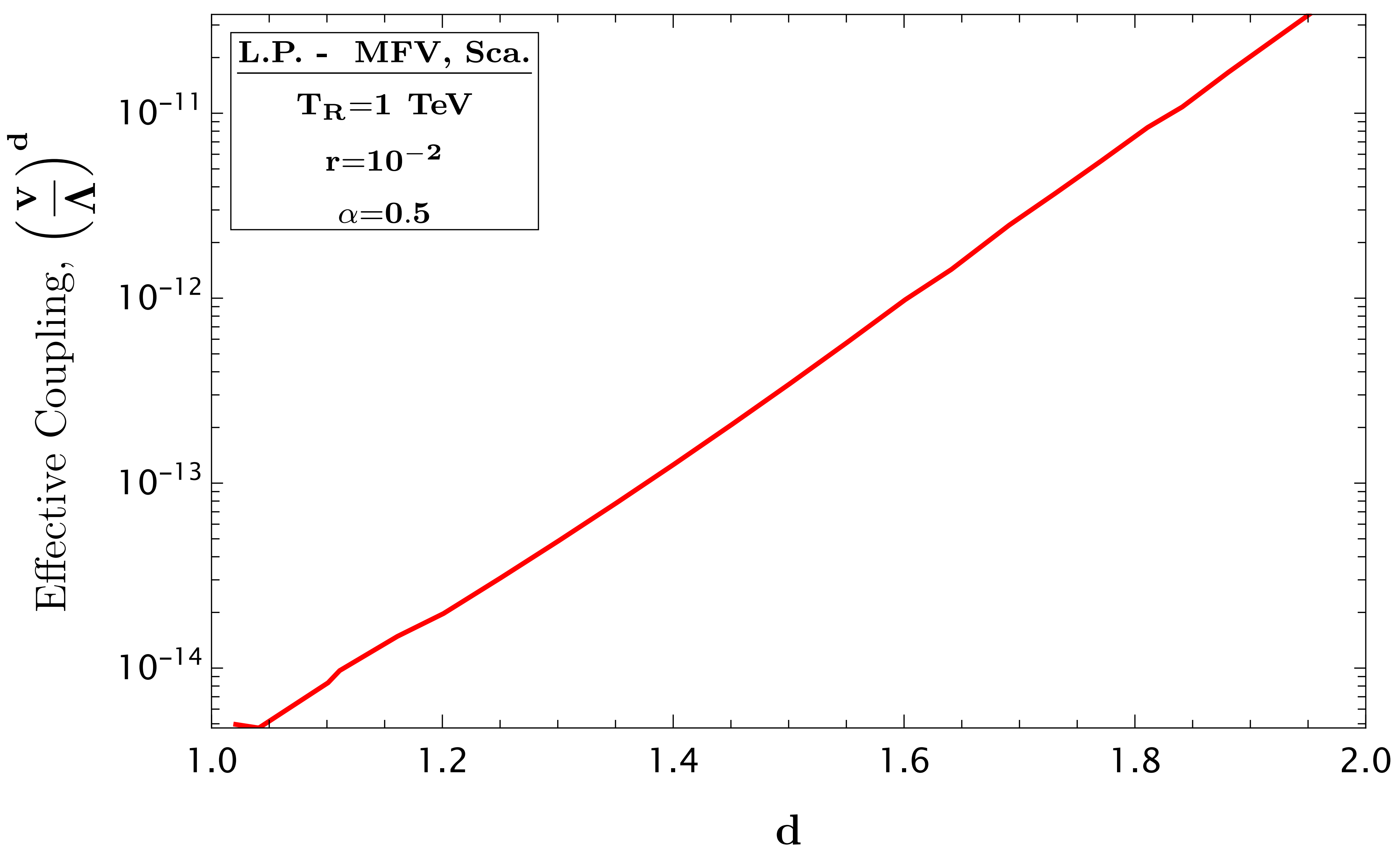
scalar rho dominant



vector rho dominant

DM-SM Couplings





$$\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{D-4}}\,\mathcal{O}_{\rm SM}\mathcal{O}_{\rm CFT}$$

[Example: MFV Lepton Portal]

$$\Lambda = (\lambda_{\rm CFT})^{-\frac{1}{D-4}}\cdot\Lambda_{\rm CFT} \sim 10^{10} - 10^{15}\ \mathrm{GeV}$$

Observational Signatures?

- DM-SM Couplings are too weak for production at colliders, direct/indirect detection (common feature of freeze-in models)

- DM mass in the 10 keV-1 MeV range $\Rightarrow$ free-streaming at scales accessible with future improved large-scale structure data

- CFT->matter phase transition in the dark sector at $T \sim M_{\rm gap}$

- No structures smaller than Hubble scale at the time of the phase transition can be formed

- Stochastic gravitational wave production if first-order phase transition (unfortunately $\Omega_{GW} \propto (T_{\rm dark}/T_{\rm SM})^8$)

Summary

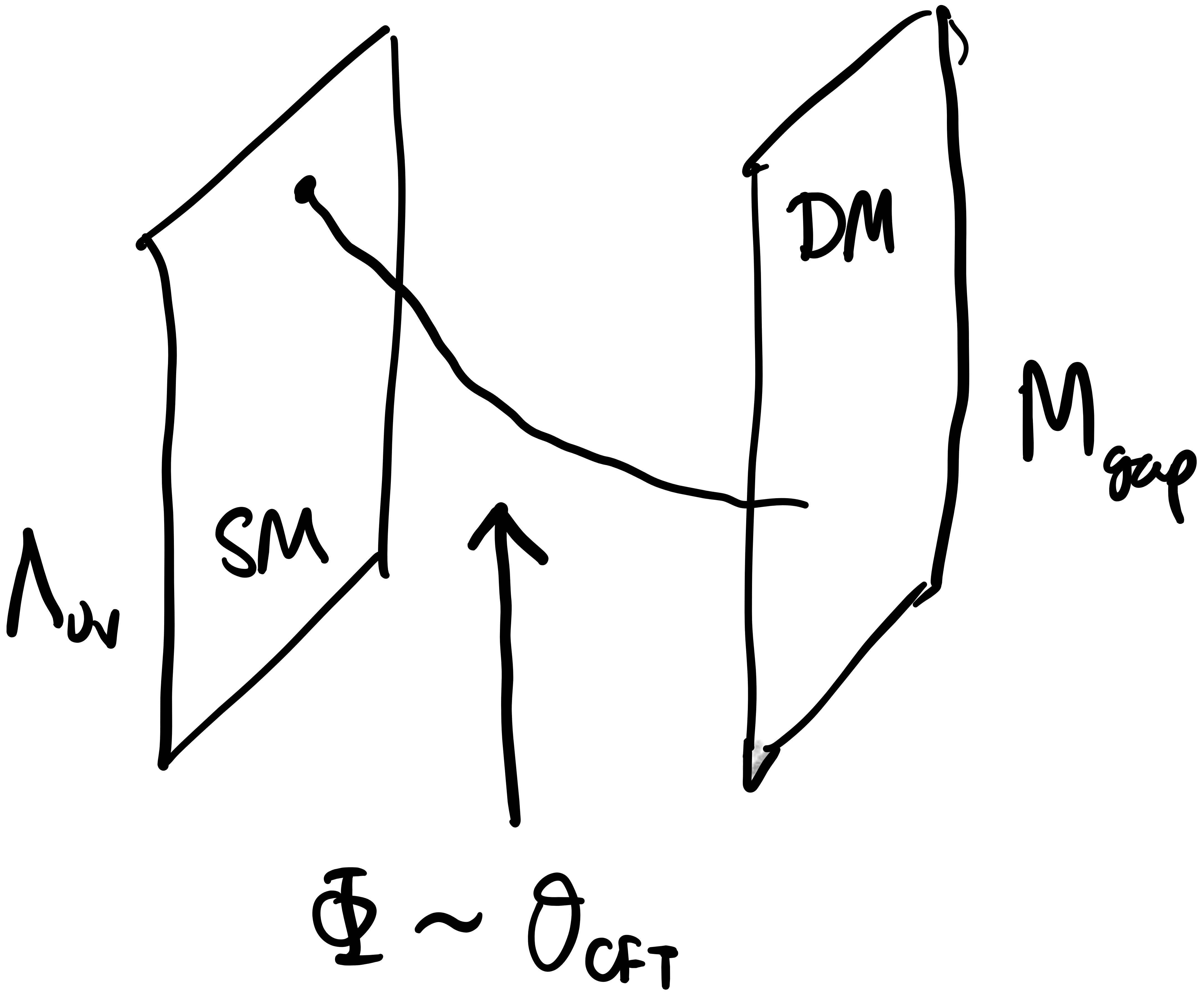
$\mathcal{O}_{\rm SM}$	DM Mass (Scalar Mediator)	DM Mass (Vector Mediator)	Dominant CFT Deformation	Dominant Production Mode
$H^\dagger H$	0.4 - 1.2 MeV	40 - 400 keV	Tree-level	$h \to$ CFT
$HQ^\dagger q$	1st: ~~SN~~ All: 0.1 - 1 MeV MFV: 0.5 - 5 MeV	1st: ~~SN~~ All: 50 - 200 keV MFV: 0.1 - 1 MeV	Radiative mixing	$q\bar{q} \to$ CFT
$HL^\dagger \ell_R$	1st: ~~WDM~~ All: 3 - 10 keV MFV: 10 - 100 keV	1st: ~~WDM~~ All: ~~WDM~~ MFV: ~~WDM~~	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

5D Dual: Relevant Dilaton

[work in progress with Lillian Luo]

- AdS/CFT correspondence indicates that the above setup has a 5D dual: AdS slice, SM on UV brane, DM IR-localized
- $\mathcal{O}_{\rm CFT}$ 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
- Realized explicitly in “Relevant Dilaton Stabilization” models (constructed for EW/ Planck hierarchy stabilization)

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



5D Dual: Relevant Dilaton

- In relevant dilation model, bulk action is

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

$$V_{\rm UV}(\Phi) = \frac{1}{2}m_{\rm UV}\Phi^2 + \gamma k^{5/2}\Phi,$$

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

- The UV-brane tadpole term serves as a source for the bulk field

- Minimizing the bulk action fixes the location of the IR brane (or equivalently dilation vev):

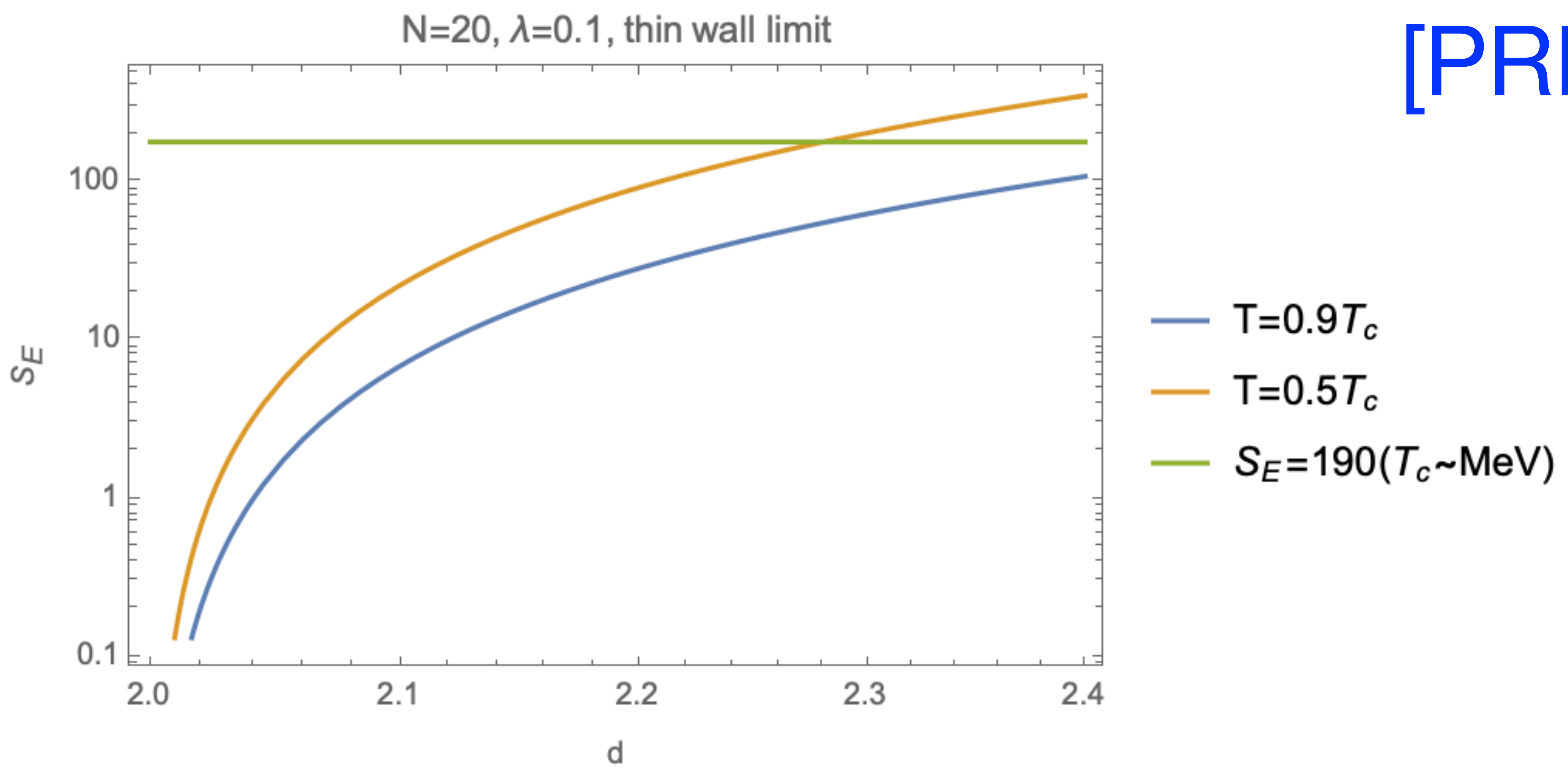
- $\chi \equiv ke^{-ky_c}$ $\qquad \langle\chi\rangle = k\left(\frac{\lambda_{2\nu}\nu}{2\lambda}\right)^{1/(4-2\nu)}$ $\qquad \longleftrightarrow \qquad$ $M_{\rm gap} = \left(\frac{\lambda_{\rm CFT}}{\Lambda_{\rm CFT}^{d-2}}v^2\right)^{\frac{1}{4-d}}$

$$\nu \equiv \sqrt{4 + m^2/k^2}$$

in COFI (Higgs portal)

5D dual: Phase Transition

[PRELIMINARY!]



- Preliminary conclusion: First-order transition completes promptly at $T_{PT} \sim M_{\text{gap}}$
- 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 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-10 MeV range
- Very feeble interactions of DM with SM, but large-scale structure signatures are possible
- Dark Sector phase transition/Gravitational wave production can be studied using 5D dual