Conformal Freeze-in of Light Dark Matter

Sungwoo Hong

KAIST

Light Dark World International Forum 2022

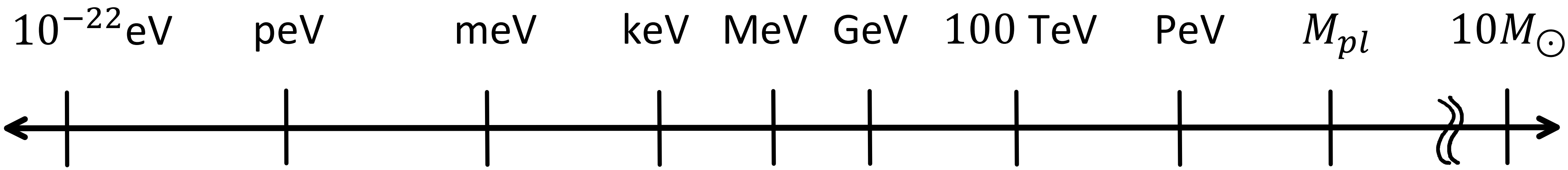
Based on works with
Gowri Kurup and Maxim Perelstein (1910.10160, 2207.10093)
Wen Han Chiu and Liantao Wang (2209.10563)

Dark Matter

We are very excited and desperate!

Enormous Efforts to Uncover **Dark Matter**

Theory : Majority of works assumes **DM** = Particle (-like)



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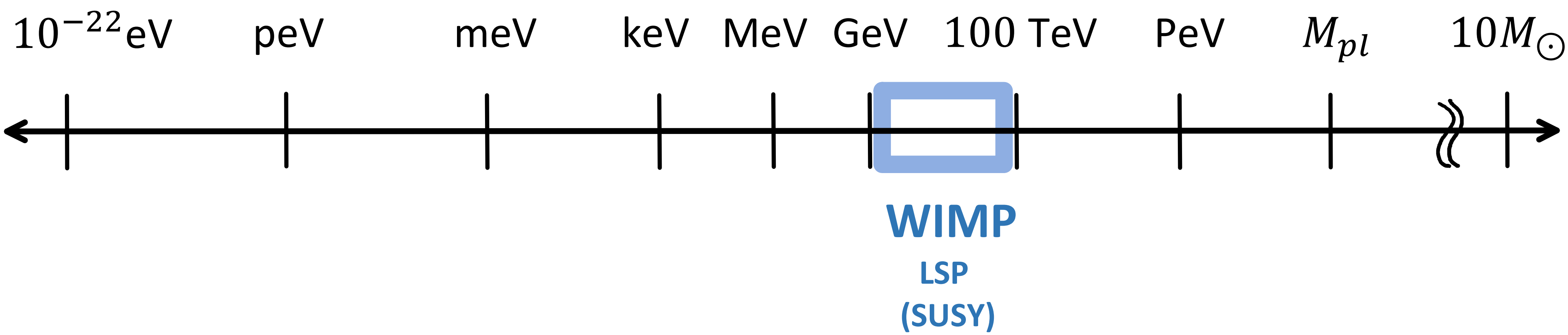

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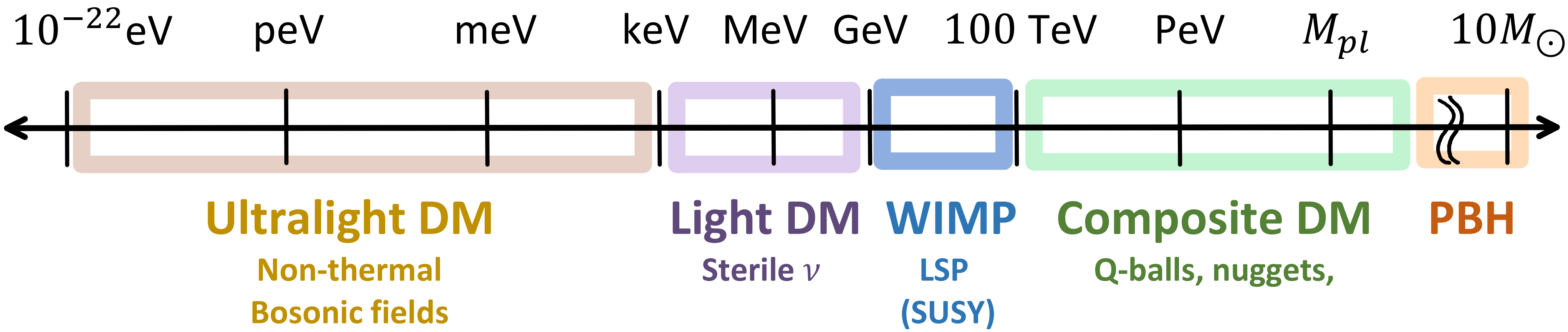
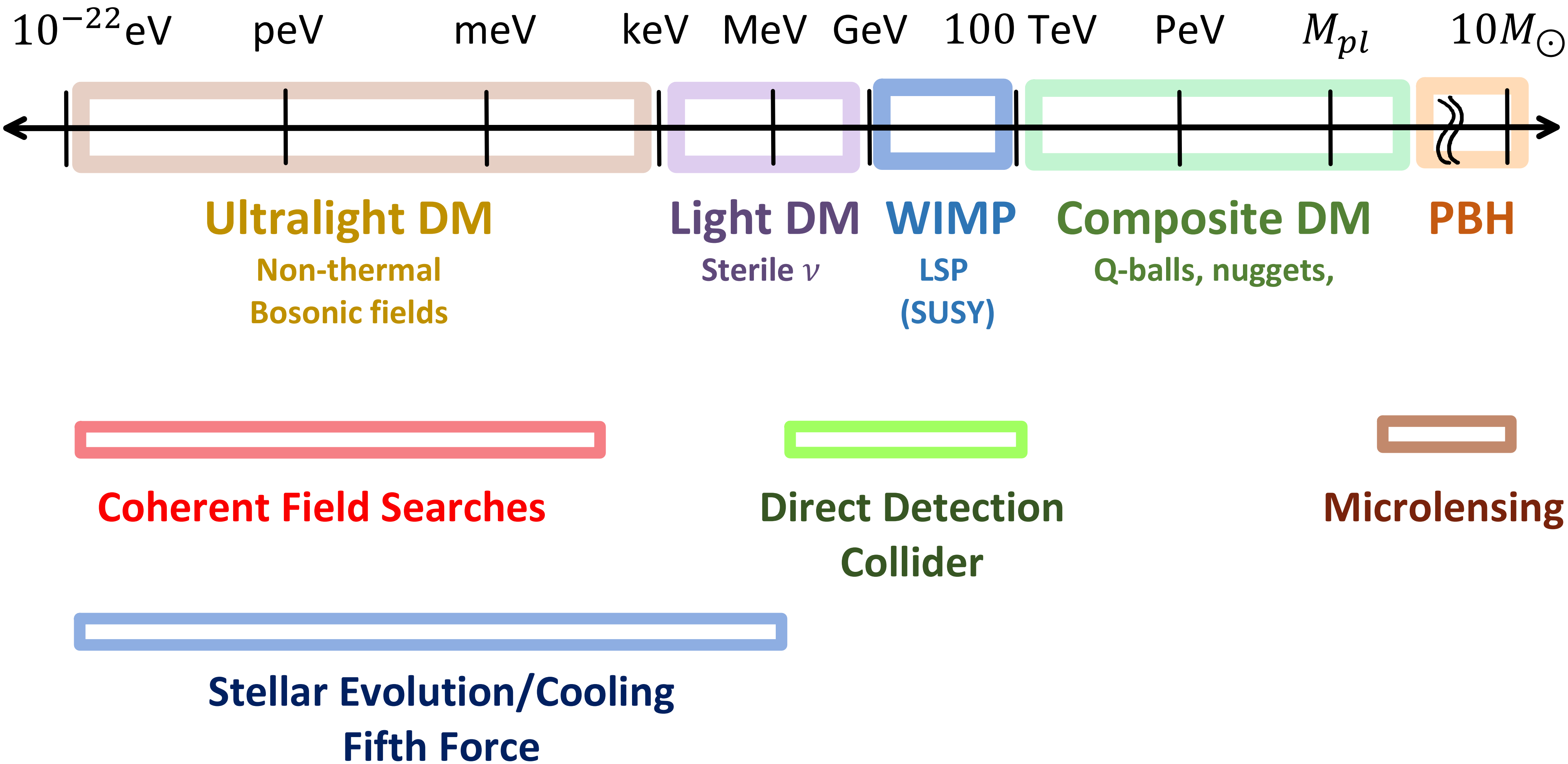


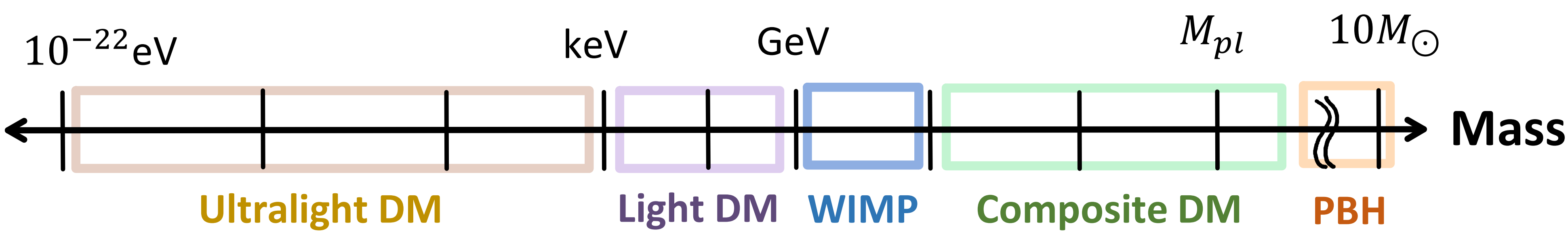
Enormous Efforts to Uncover **Dark Matter**

- Experiments : Diverse approaches, different scales, many of them



Uncovering New Lampposts for DM

Let's be even more **creative**!



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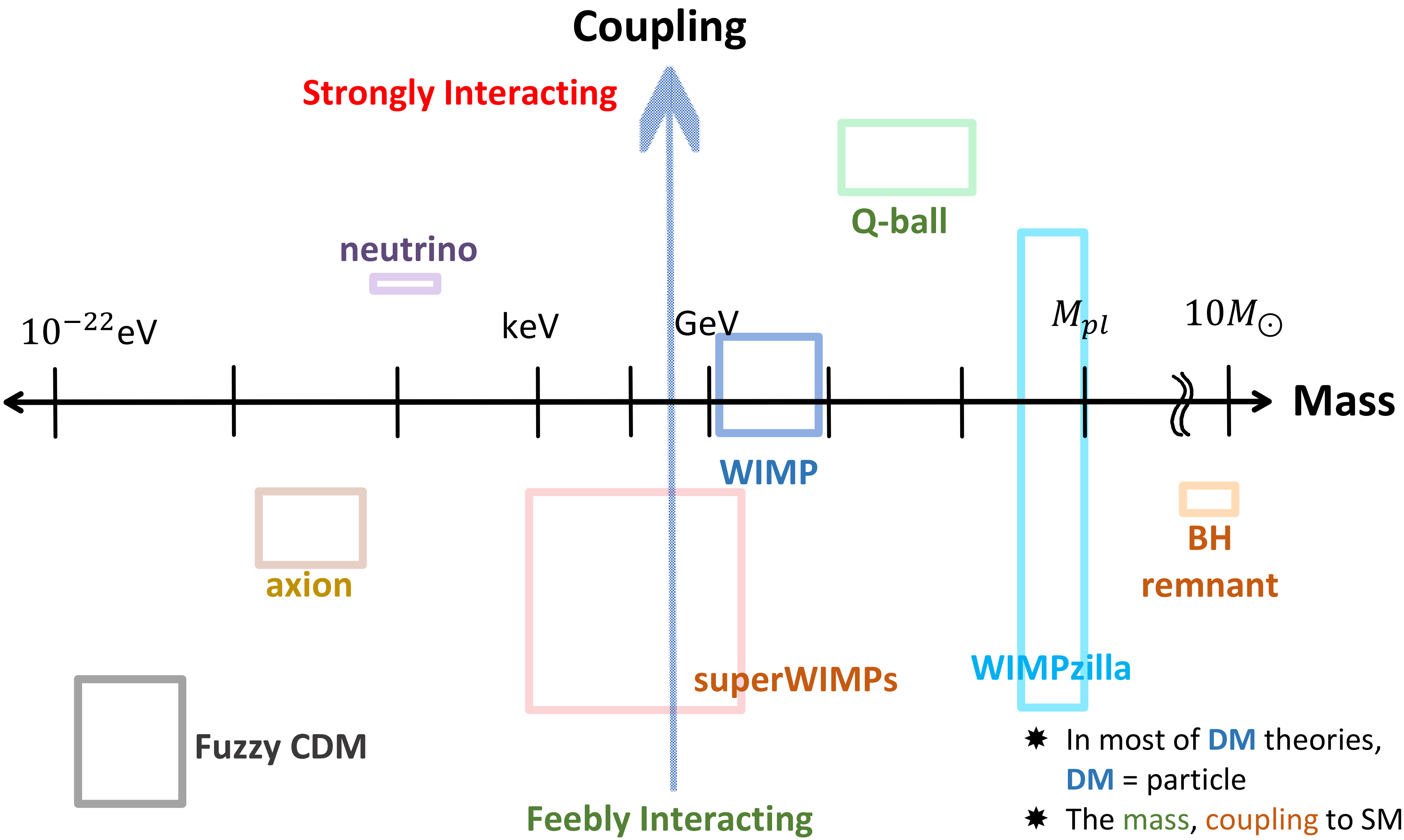

- In most of DM theories, DM = particle
- The mass, coupling to SM, spin etc are put by hand

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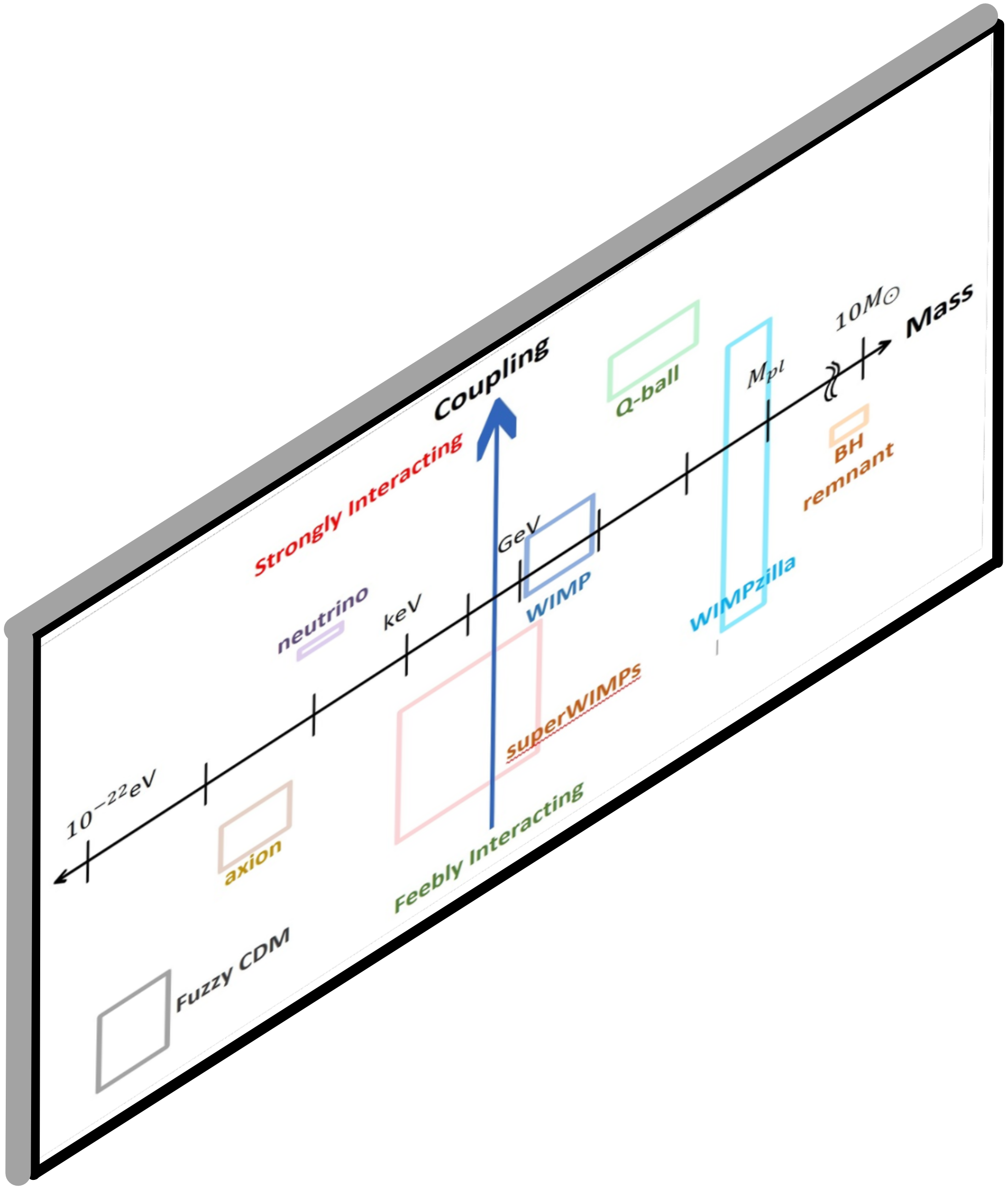

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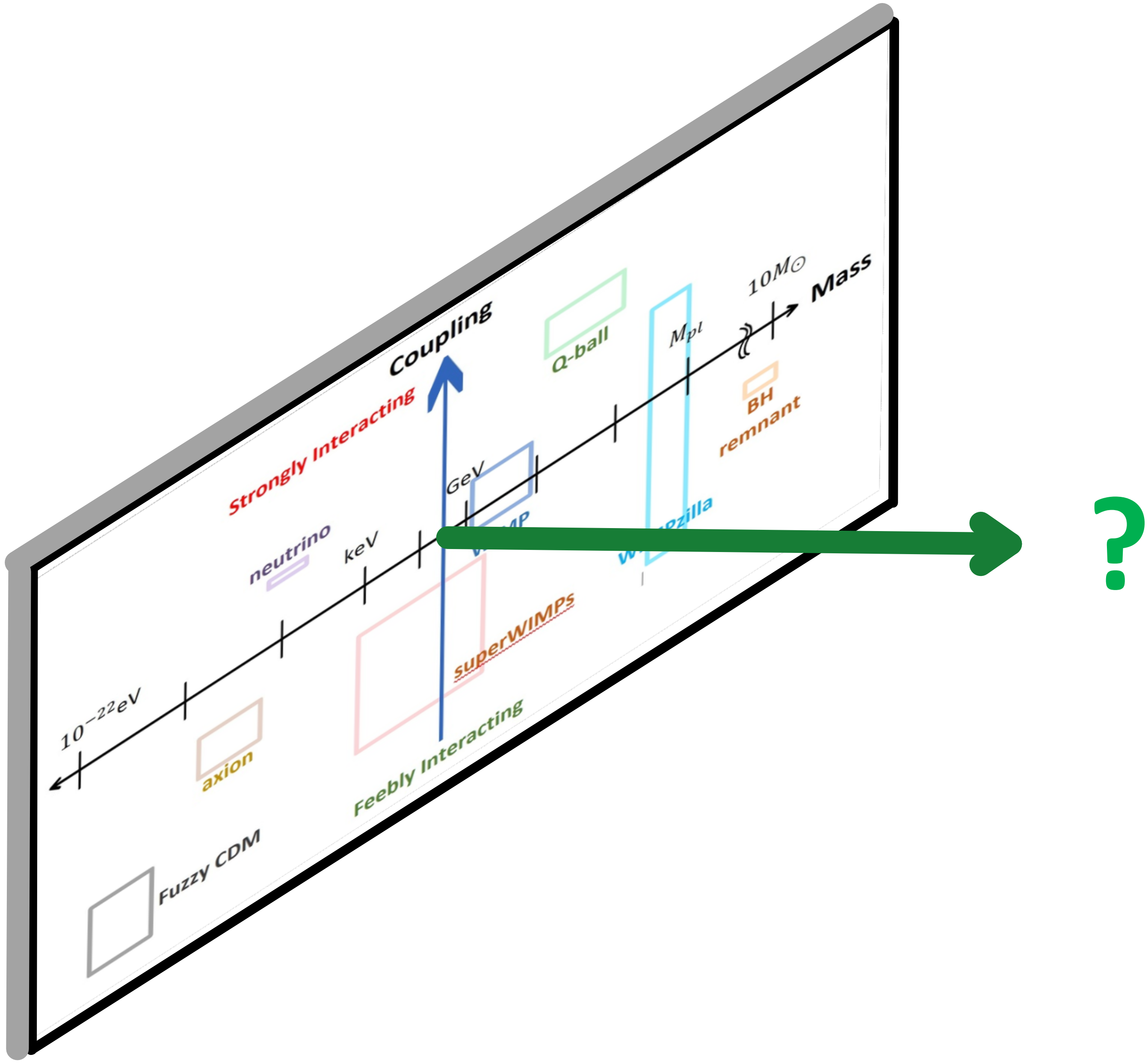

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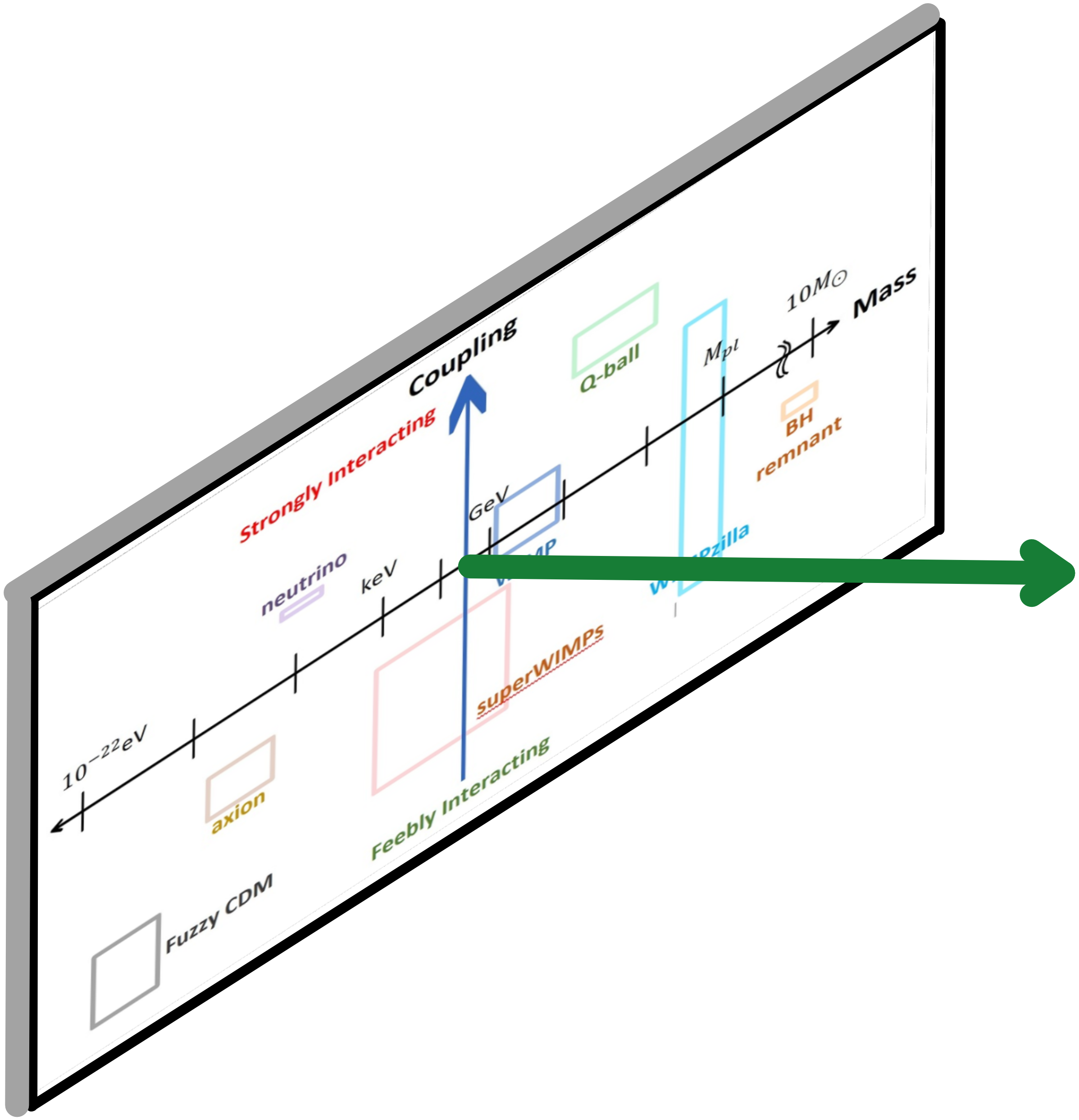

Conformal Freeze-In (COFI)

or

Continuum DM

or

?

Outline

1. Introduction to Conformal Freeze-In

2. Robustness of COFI mechanism

3. COFI Phenomenology
   - DM Self-Interaction, WDM, Star Cooling

4. Conclusion and Outlook

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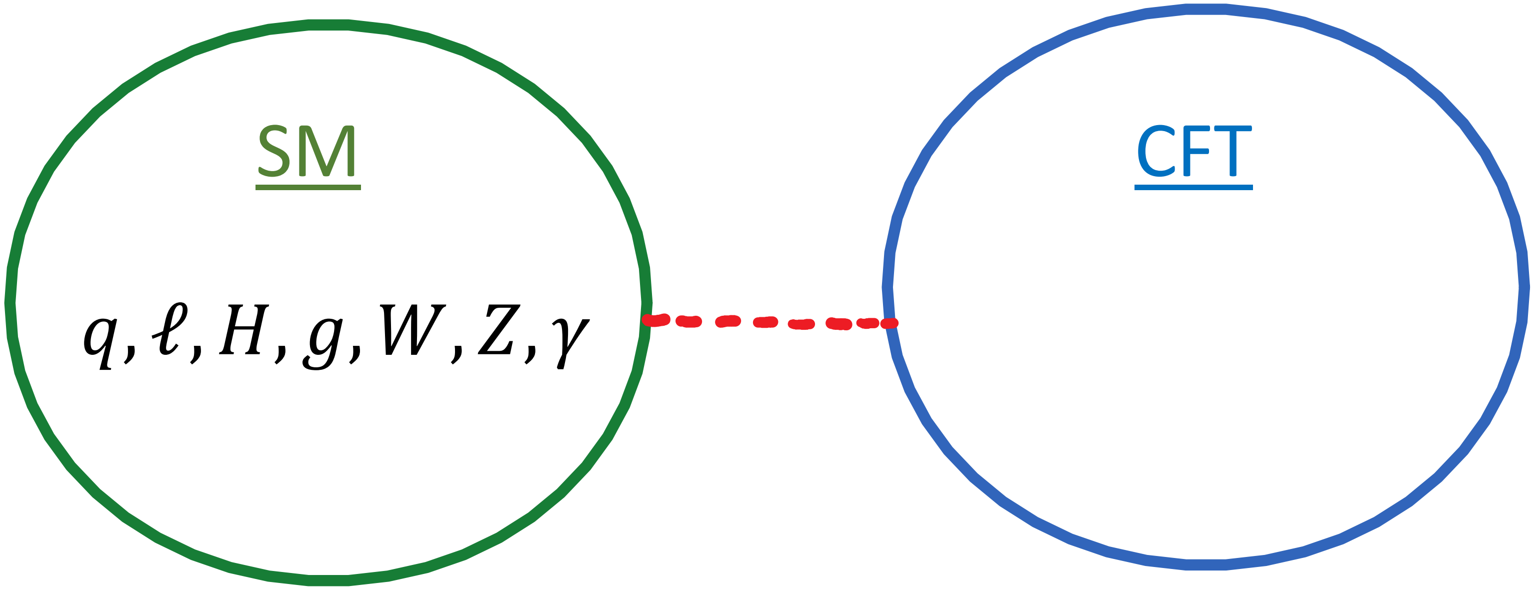
Conformal Freeze-In (COFI)



$$\mathcal{L} \supset \lambda\, \mathcal{O}_{SM} \mathcal{O}_{CFT}$$

Conformal Freeze-In (COFI)

(Q) Why Conformal Dark Sector?

(A1) CFT is mathematically well-defined QFT

UV CFT 

Not a particle

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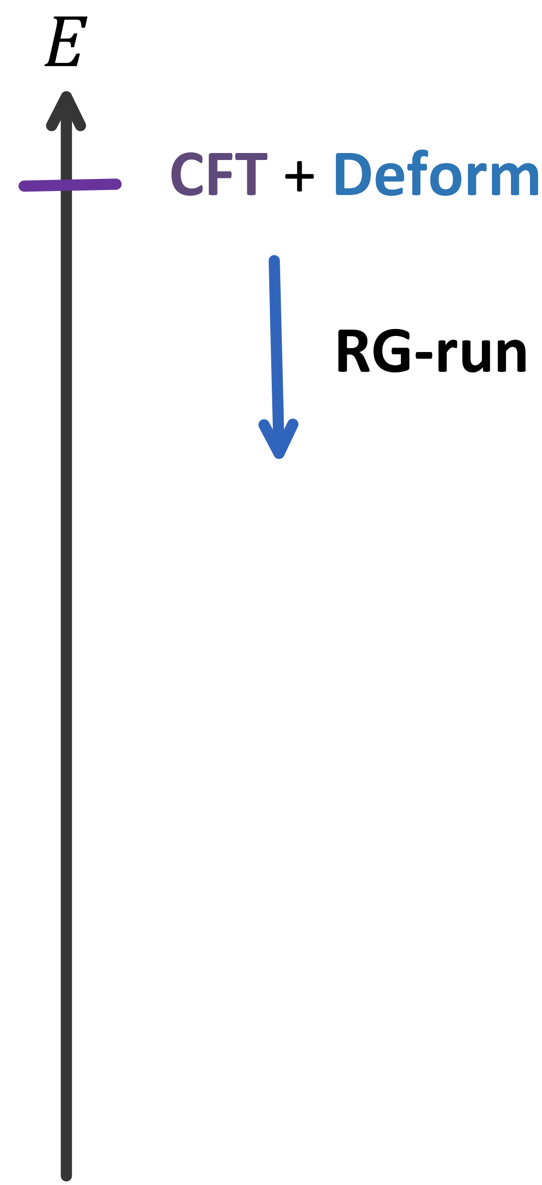

UV CFT **QFT** particle

Not a particle

***Deformation**

small breaking of
conformal invariance

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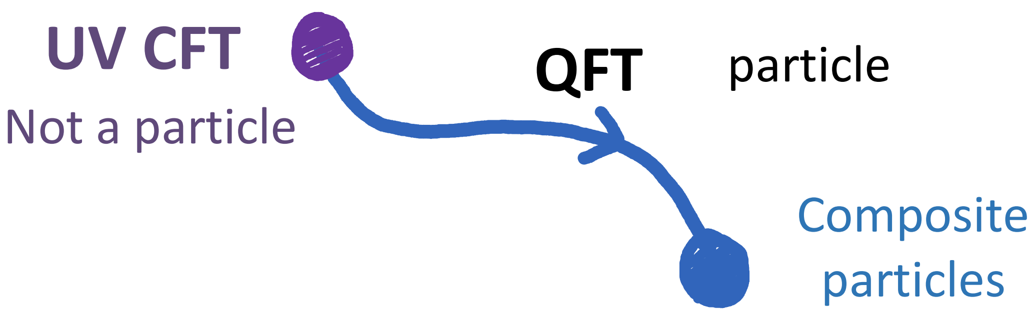

<u>*Deformation</u>

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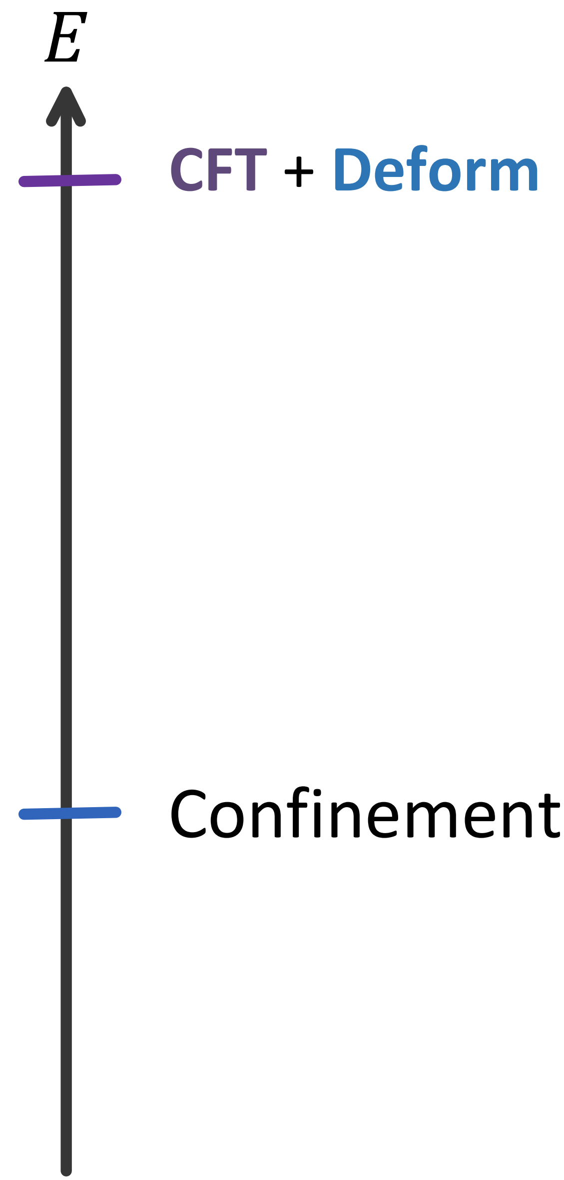

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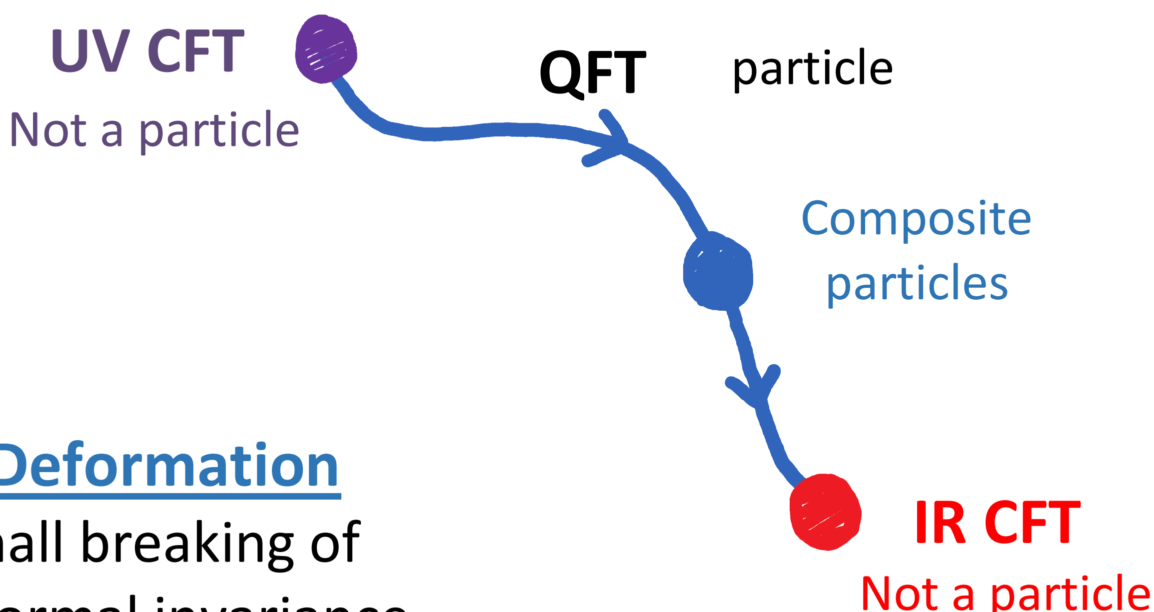

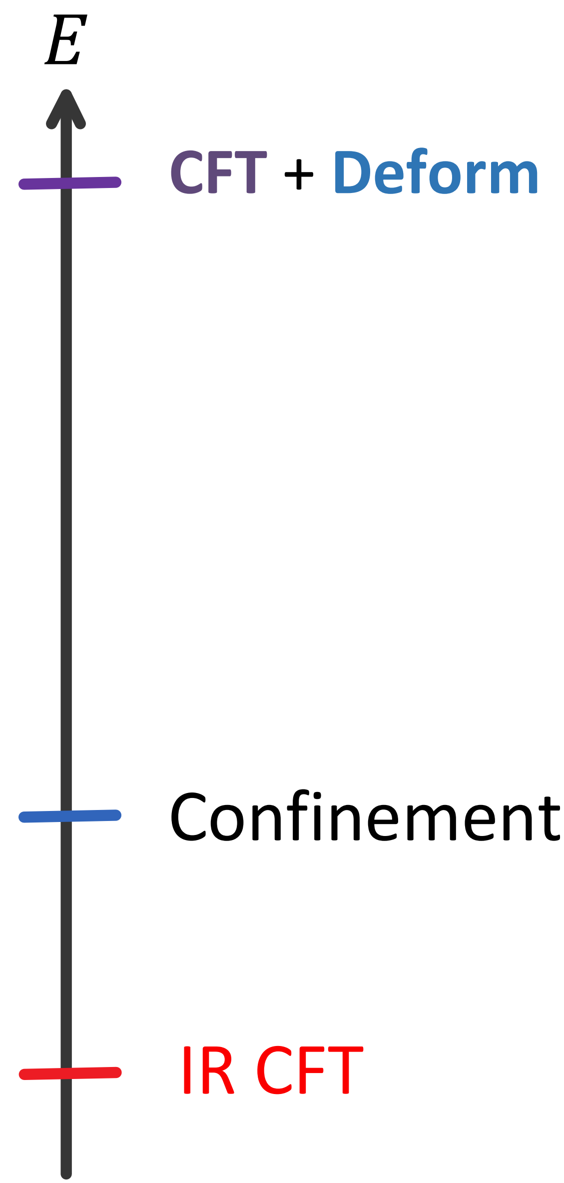

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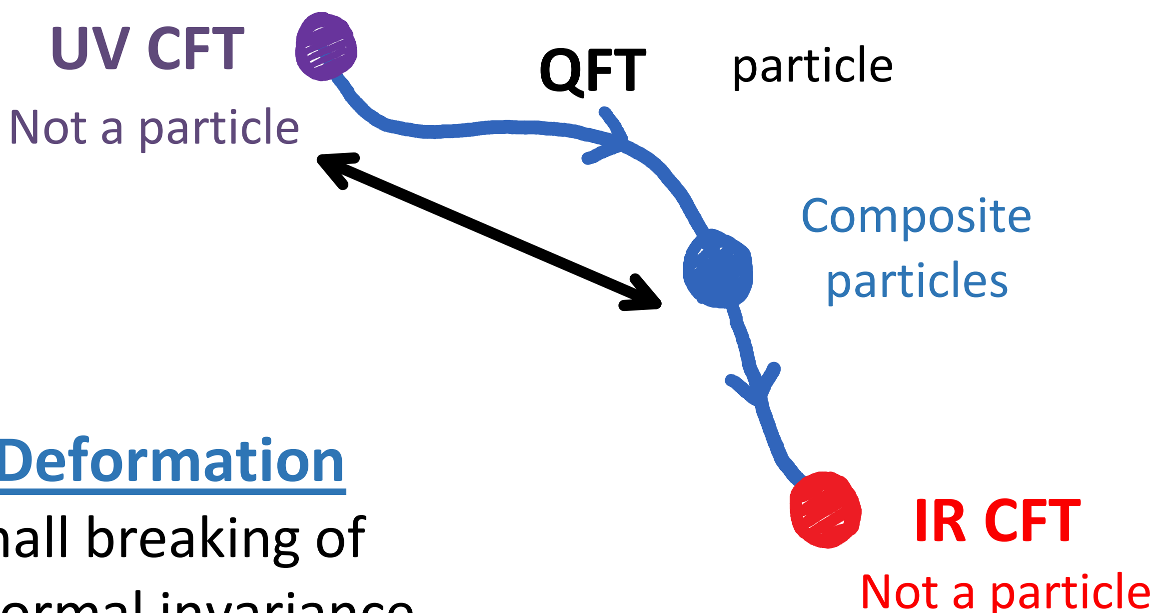

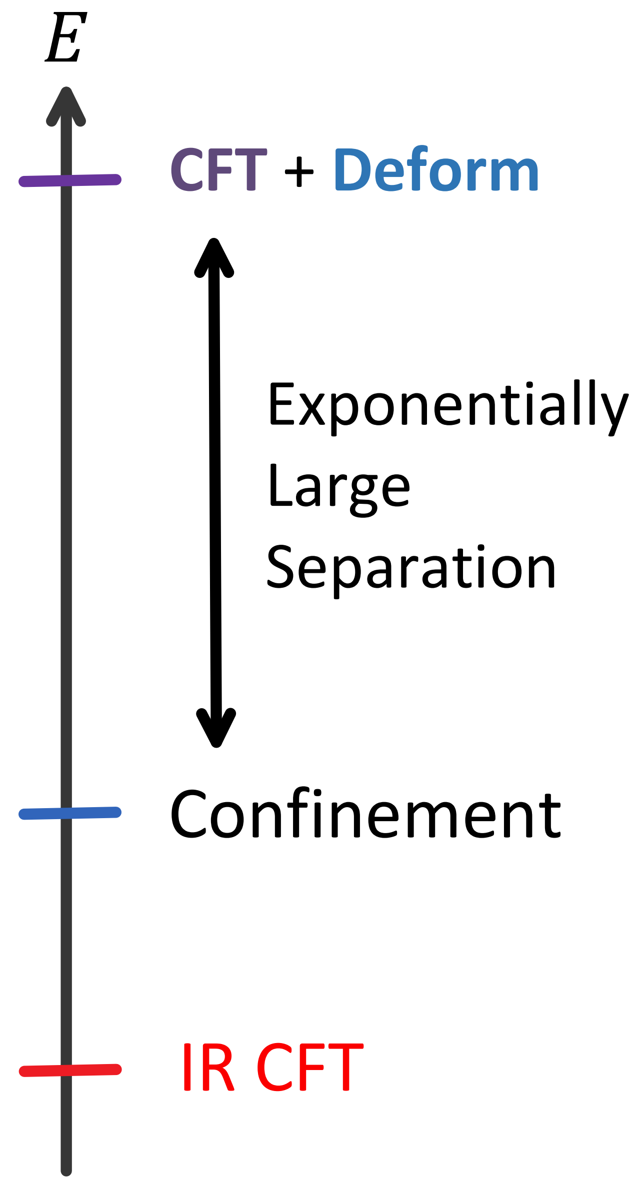

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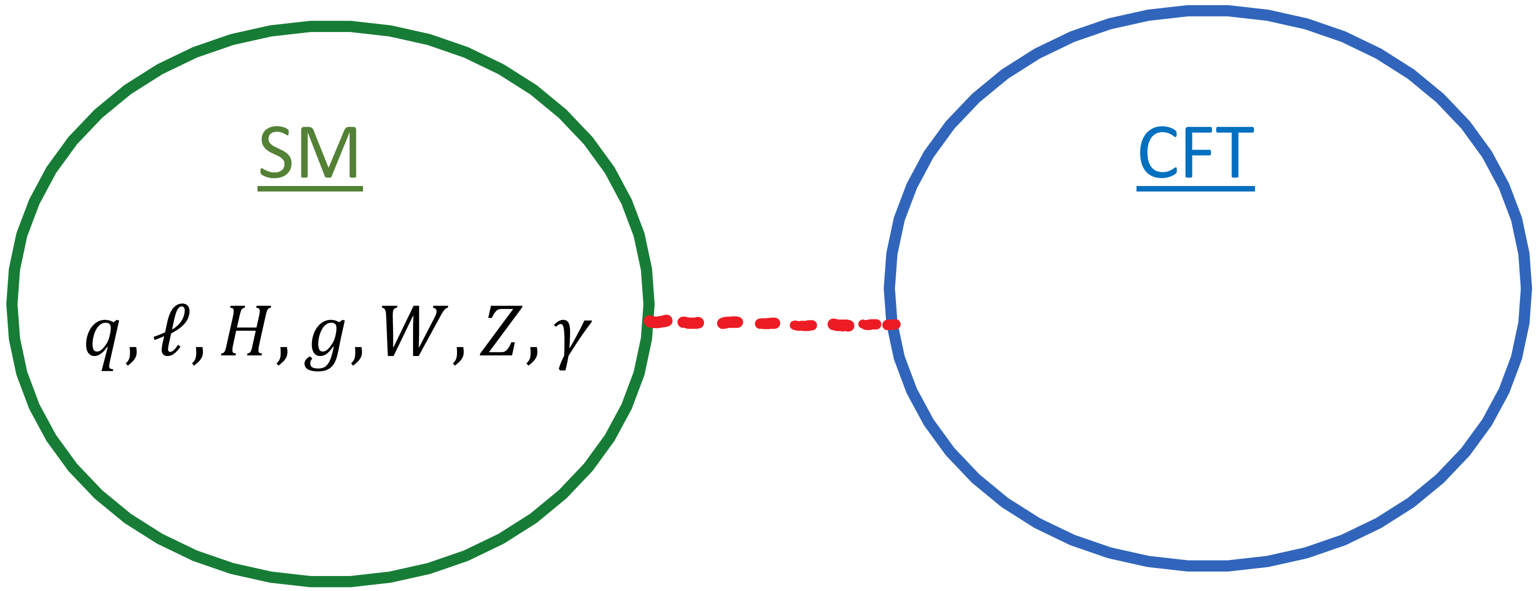
(A3) CFT can be a IR-phase of QFTs

(A4) CFT features some nice universal properties thanks to large symmetry

$$\langle O(x)O(0)\rangle = \frac{c}{|x|^{2d}}$$

(A5) AdS/CFT-correspondence: $CFT_D = AdS_{D+1}$
special class of CFTs admits a dual description in terms of gravitational theory in one higher dimension

Conformal Freeze-In (COFI)



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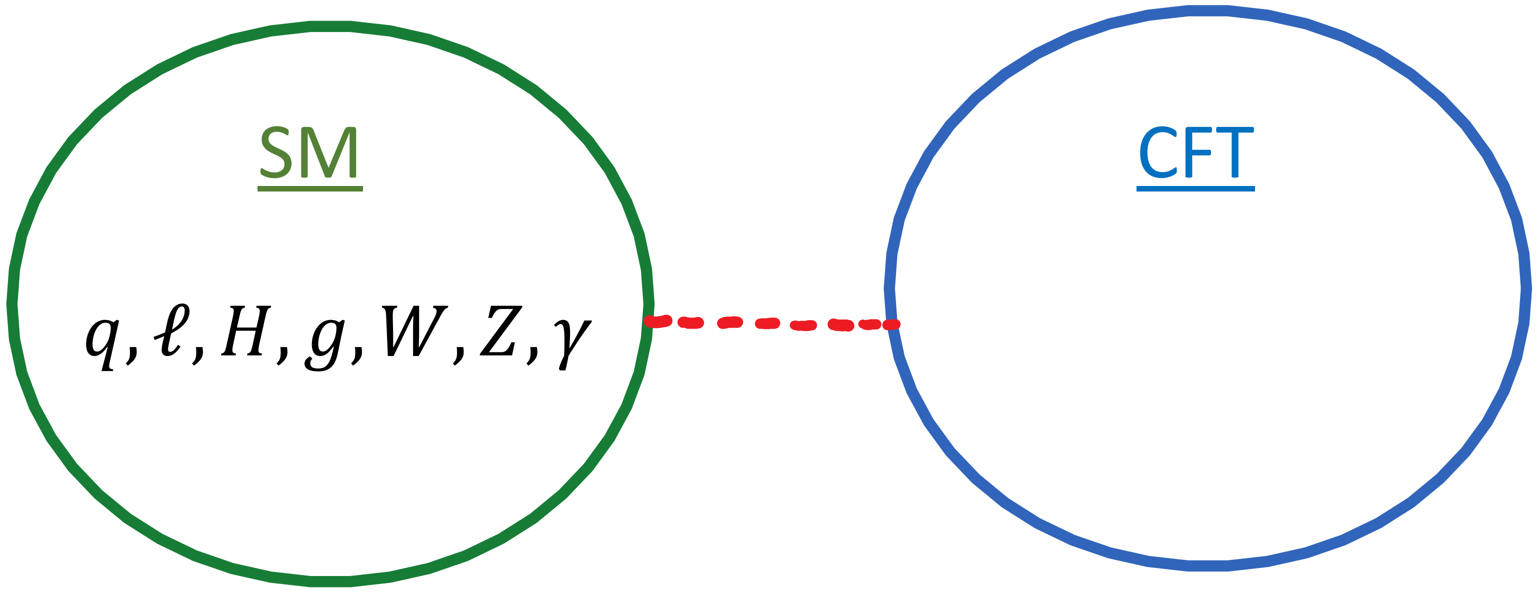

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(Q) Under what conditions can this "conformal dark sector" turn into a "dark matter sector" ?

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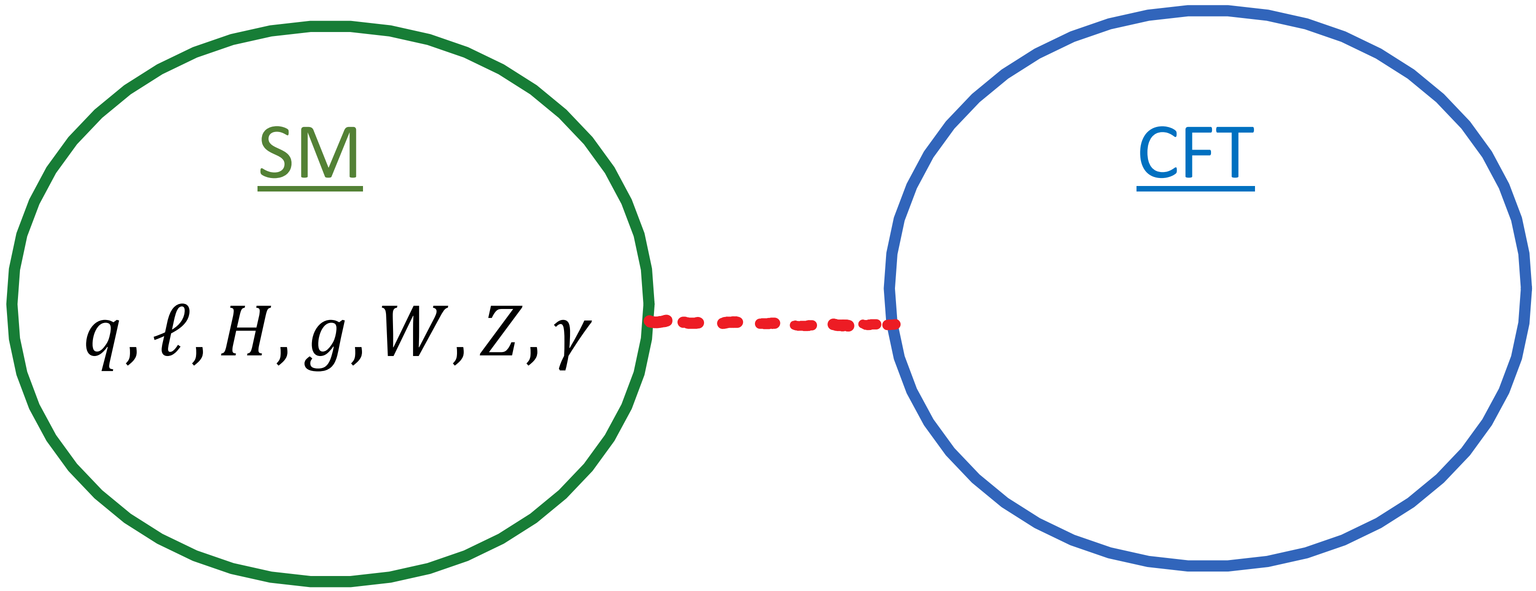

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(Q) Under what conditions can this "conformal dark sector" turn into a "dark matter sector" ?

(A) Most likely* answer: Conformal Freeze-In (COFI)

Conformal Freeze-In (COFI)

We begin with

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{D-4}} \, \mathcal{O}_{SM} \, \mathcal{O}_{CFT} \ , \qquad D = d_{SM} + d_{CFT}$$

Conformal Freeze-In (COFI)

We begin with

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{D-4}}\, \mathcal{O}_{SM}\, \mathcal{O}_{CFT} \ , \qquad D = d_{SM} + d_{CFT}$$

This simple interaction does MANY things:

(i) It breaks CFT

(ii) This breaking eventually leads to generation of mass scale

CFT (radiation) $\rightarrow$ Dark Matter

$m_g \ll m_{SM}$ $\rightarrow$ Light DM (keV - MeV)

(iii) Production of dark sector via conformal freeze-in

(vi) Observations

Consider $\mathcal{O}_{SM} = H^{+}H$

At $v < E < \Lambda$

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{d-2}} H^{+}H\, \mathcal{O}$$

- Assume: this is the only CFT breaking term
  (in the limit $\lambda \to 0$ we have a decoupled exact CFT + SM)

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At $E < v$ we get

$$\mathcal{L} \sim \frac{\lambda \, v^2}{\Lambda^{d-2}} \, \mathcal{O} \sim c \, \mathcal{O}$$

- A scalar deformation (to CFT) is induced by the EWPT.
- After this, CFT starts RG-running

Consider $\mathcal{O}_{SM} = H^{+}H$

At $E < v$ we get

$$\mathcal{L} \sim \frac{\lambda\, v^2}{\Lambda^{d-2}}\, \mathcal{O}$$

- For $d < 4$, the effect of deformation grows in the IR

- Eventually, it becomes $\mathcal{O}(1)$ effect at

$$m_g \sim \left(\frac{\lambda\, v^2}{\Lambda^{d-2}}\right)^{1/(4-d)}$$

Consider $\mathcal{O}_{SM} = H^{+}H$

At $E < m_g$

- CFT goes through a gap-creating phase transition (PT)

- Possible IR phases ?

(i) Confinement

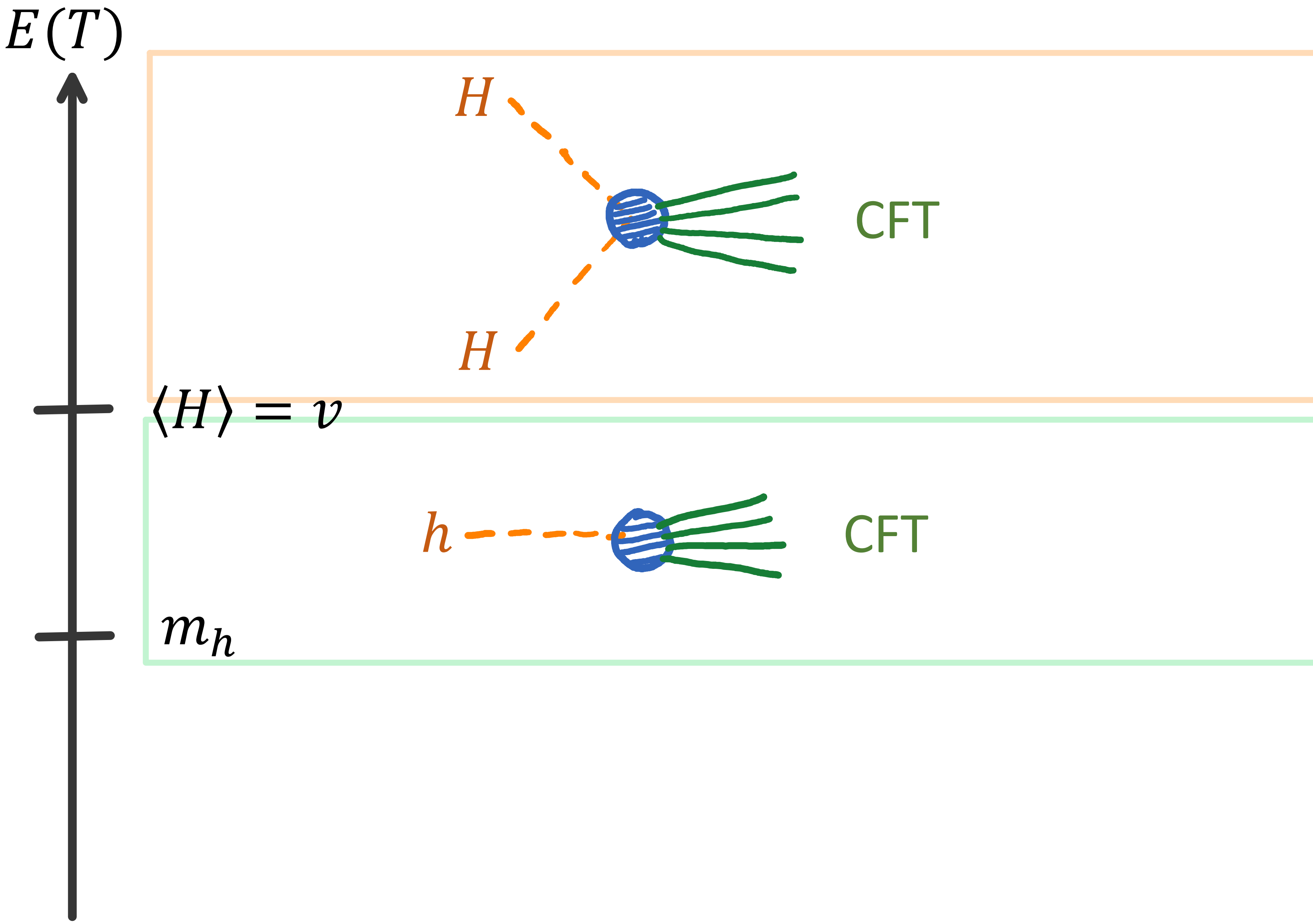
  - most probable/standard
  - spectrum : discretum of composite hadrons
  - DM = light stable states, e.g. PNGB

(ii) Gapped Continuum (with C.Csaki, G.Kurup, S. Lee, M. Perelstein, W.Xue)

  - more exotic possibility but many interesting features!
  - UV-completion with non-thermal version of continuum DM ? (with G.Kurup, S.Lee, Y.Lee)

COFI: Freeze-in Production

$$\mathcal{L} \supset \lambda\, H^{\dagger} H \mathcal{O}_{CFT}$$



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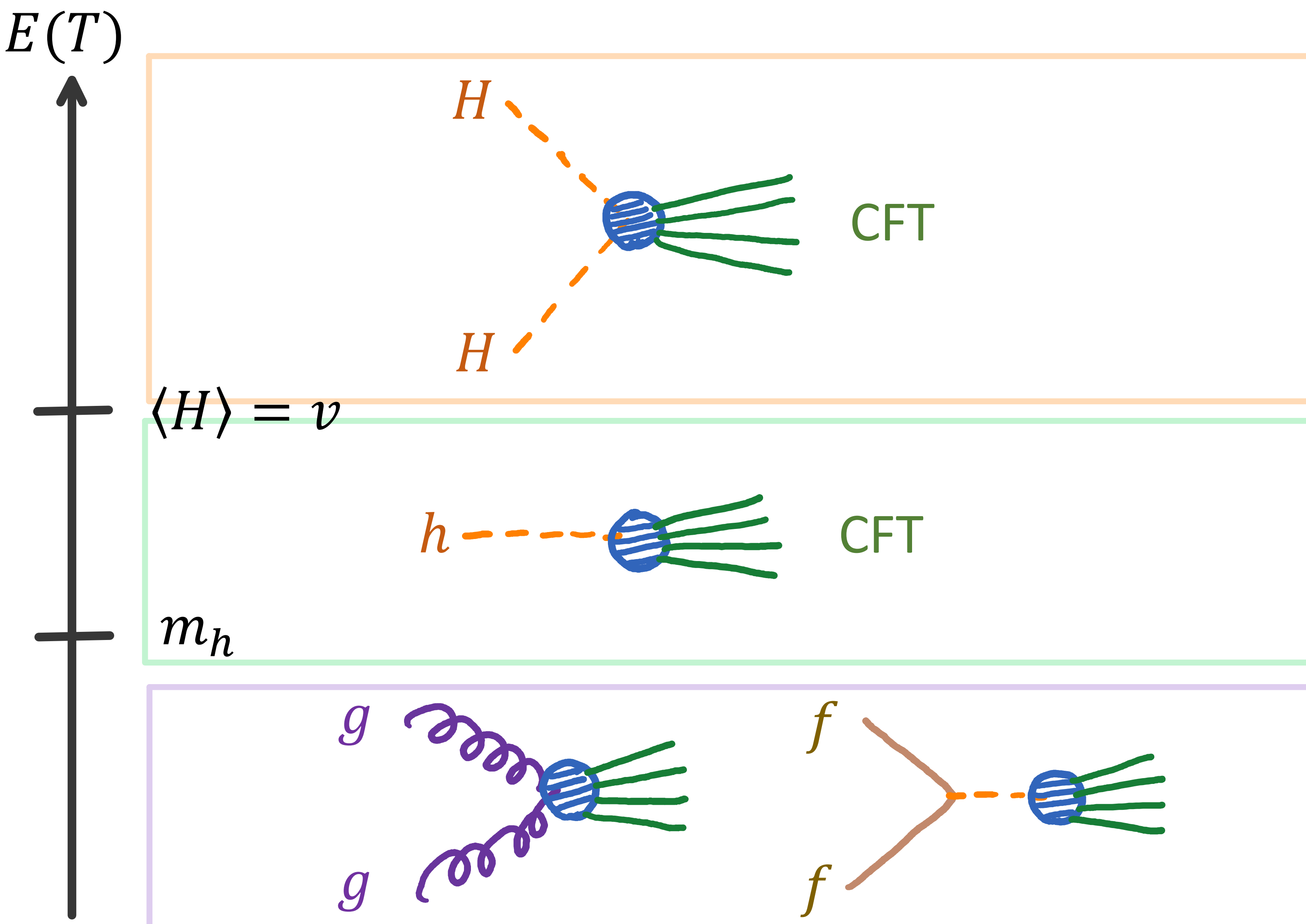

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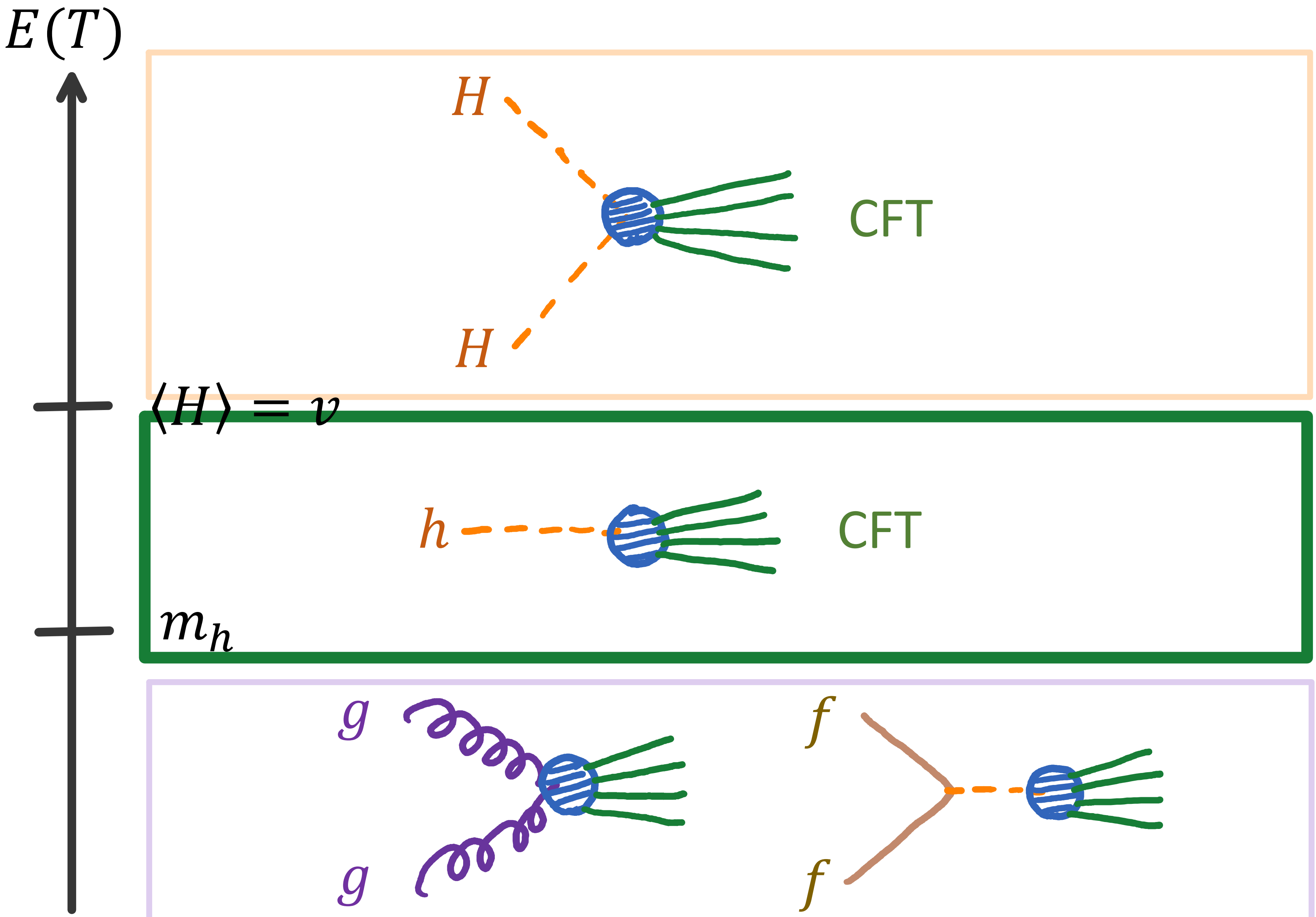
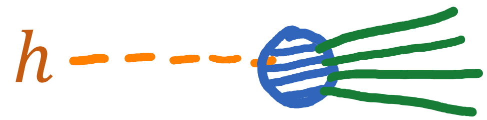


COFI: Computation

$\mathcal{L} \supset \lambda\, H^\dagger H \mathcal{O}_{CFT}$



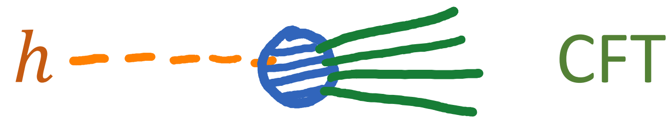
CFT

- **Conformal Freeze-In** completely calculable theory of **DM**

- **Conformal Freeze-In** makes precise predictions!

COFI: Computation

$$\mathcal{L} \supset \lambda\, H^{\dagger} H\, \mathcal{O}_{CFT}$$

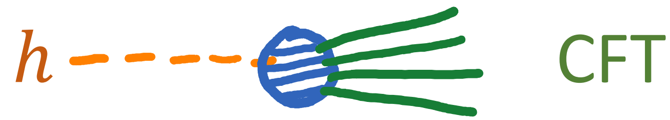


$$\frac{d\rho_{dark}}{dt} + 4H\rho_{dark} = \Gamma_E\,(SM \to CFT)$$: Boltzmann Equation

$$(\,\nabla_\mu T^\mu_\nu = \Gamma_E\,, \qquad T^\mu_\mu = 0)$$

COFI: Computation

$$\mathcal{L} \supset \lambda\, H^\dagger H \mathcal{O}_{CFT}$$



$$\frac{d\rho_{dark}}{dt} + 4H\rho_{dark} = \Gamma_E\,(SM \rightarrow CFT) \quad : \quad \text{Boltzmann Equation}$$

$$\Gamma_E\,(SM \rightarrow CFT) = \int\int d\Pi_h \frac{d^4 P_{CFT}}{(2\pi)^4} \langle \mathcal{O}^\dagger \mathcal{O} \rangle (\boldsymbol{P_{CFT}})\, f_h (2\pi)^4 \delta^4 (p_h - P_{CFT}) \left| \widehat{M} \right|^2$$

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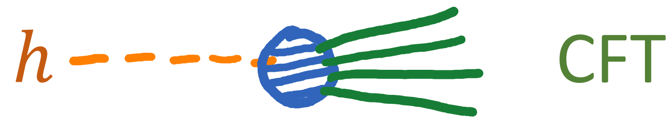

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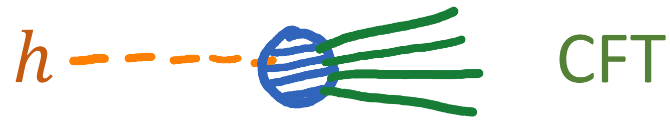
$$\rho_{dark}\,(T) = \frac{\sqrt{5} M_{pl} f_d \lambda^2}{\pi^{3/2}\sqrt{g_*}\, v}\, m_h^{2d-4} T^4 \left(\frac{v^3}{T^3} - 1\right)$$

$$f_d = \frac{\sqrt{\pi}}{(2\pi)^{2d}} \frac{\Gamma\left(d + \frac{1}{2}\right)}{\Gamma(\mathrm{d}-1)\Gamma(2\mathrm{d})}$$

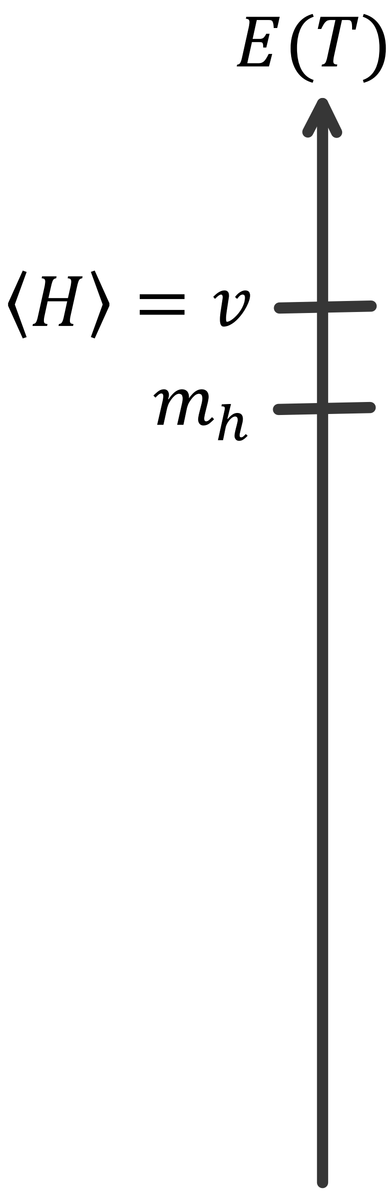
COFI: Necessity of Mass Gap

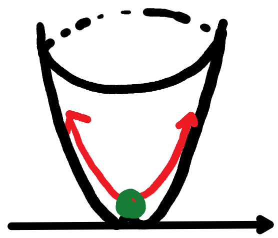
$\mathcal{L} \supset \lambda\, H^{\dagger} H \mathcal{O}_{CFT}$



- For Dark **Matter**, $\rho \propto \frac{1}{a^3} = T^3$ vs $\rho_{CFT} \propto \frac{1}{a^4} = T^4$
- Conformal Dark Sector should be **gapped**, somehow!
- As I showed, this occurs in **COFI** automatically and elegantly!

COFI: Dynamical Gap Generation





$\mathcal{L} \supset \lambda\, H^{\dagger} H \mathcal{O}_{CFT}$

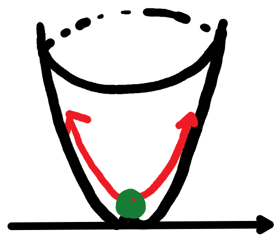
- Describes **interaction** $SM \leftrightarrow CFT$
- Production: $HH \rightarrow CFT$

COFI: Dynamical Gap Generation

$E(T)$

$\langle H \rangle = v$

m_h



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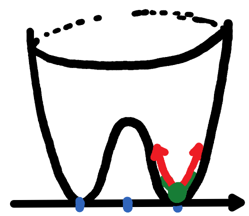

$\mathcal{L} \supset \lambda \, v^2 \mathcal{O}_{CFT}$

- **Scalar Deformation** to CFT
- $\langle \mathcal{O}_{CFT} \rangle$: order parameter for conformality lost

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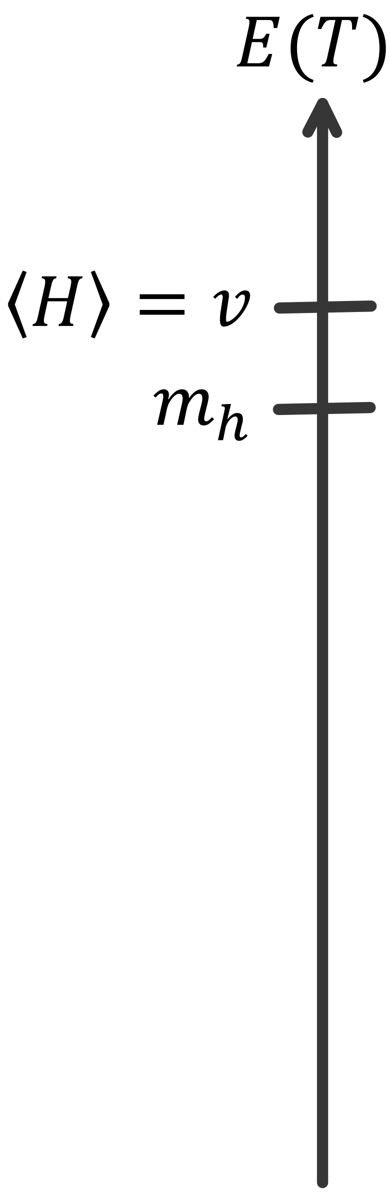

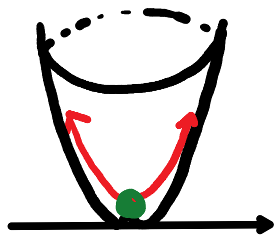

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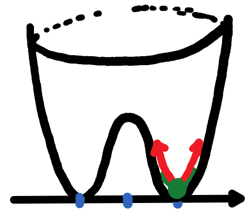

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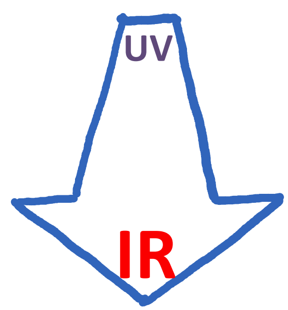

- **Scalar Deformation** to CFT
- $\langle \mathcal{O}_{CFT} \rangle$: order parameter for conformality lost
- The effect grows in IR
  $[\mathcal{O}_{CFT}] < 4$ (relevant)

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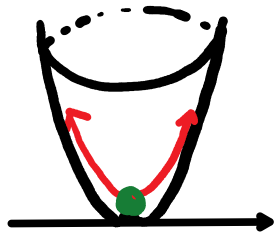
$\langle H \rangle = v$

m_h

m_{gap}



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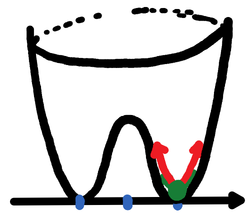

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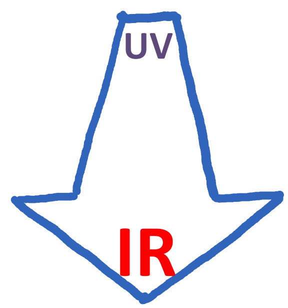
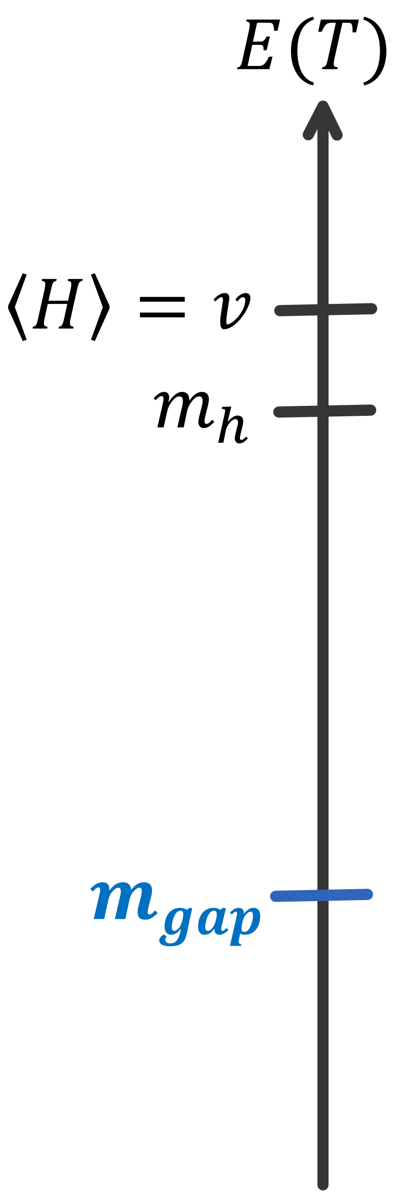


- **Scalar Deformation** to CFT
- $\langle \mathcal{O}_{CFT} \rangle$: order parameter for conformality lost
- The effect grows in IR $[\mathcal{O}_{CFT}] < 4$ (relevant)

- $E < m_{gap}$: CFT → **composite dark hadrons**
- Slow RG-running (∵ freeze-in $\lambda \ll 1$)
- $\langle \mathcal{O}_{CFT} \rangle^{1/d} = \boldsymbol{m_{gap}} \ll v$:(small) mass outcomes!

COFI: DM from Conformal Dark Sector!



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- $\rho_{dark} \propto \frac{1}{a^4} = T^4$ (Radiation)

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- Production: $h \to CFT$
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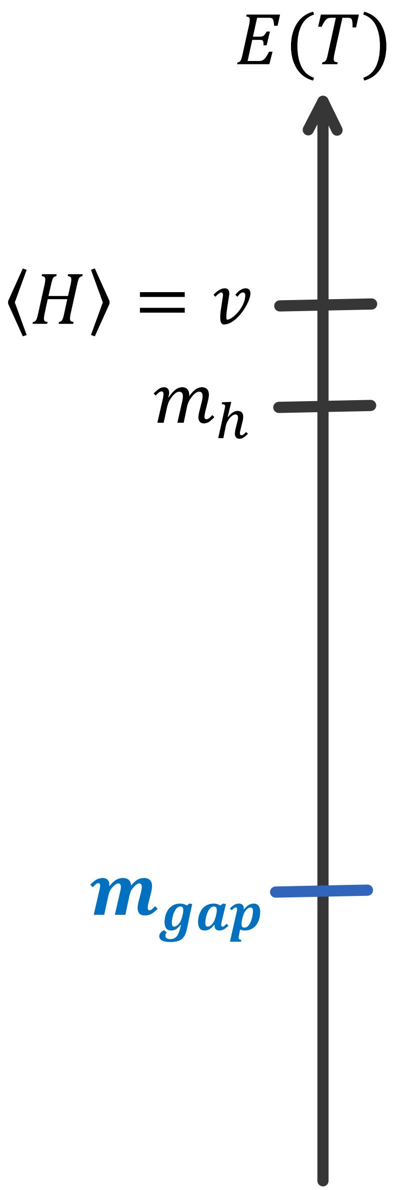

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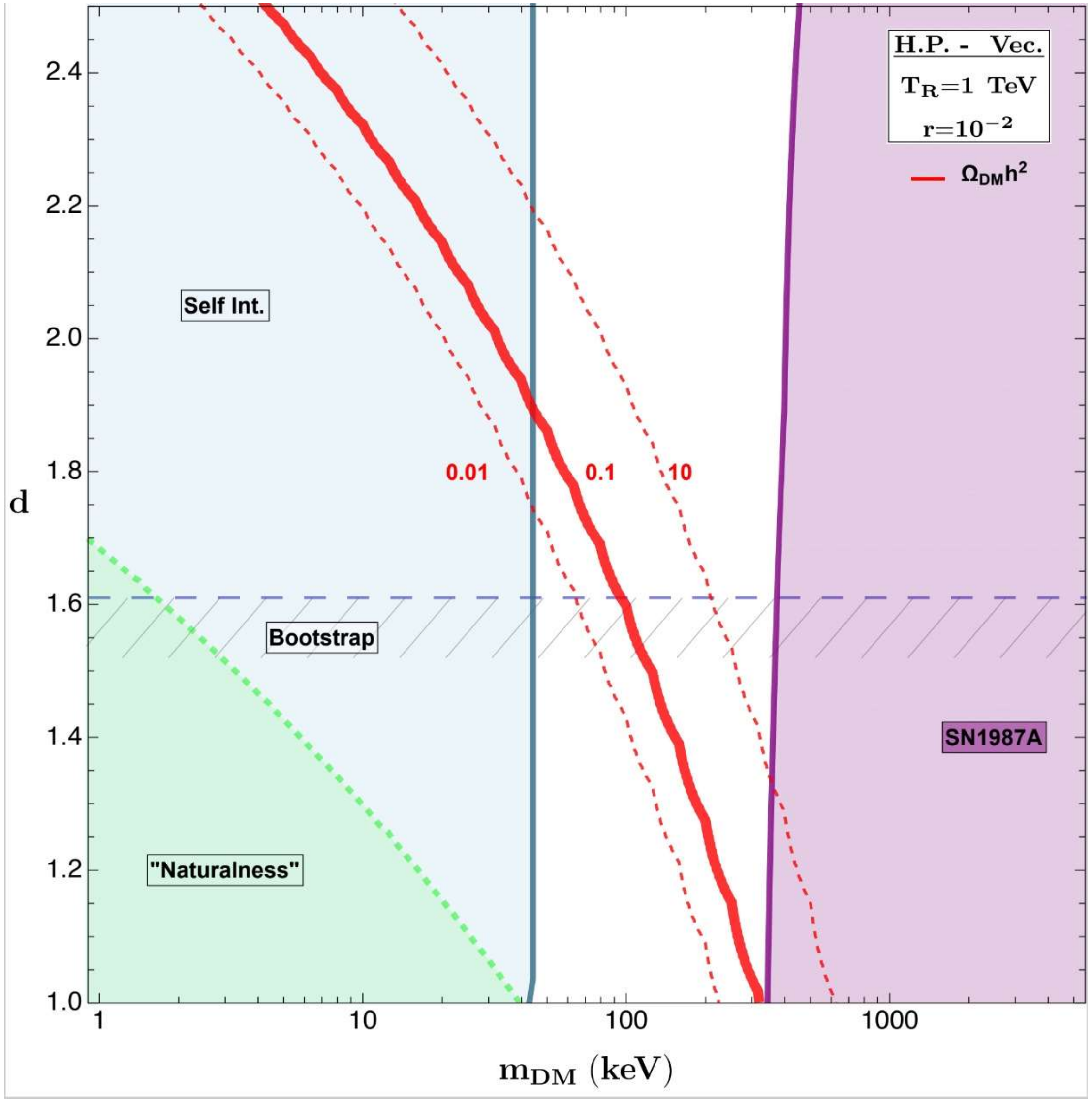
- Production: $h \to CFT$
- $\rho_{dark} \propto \frac{1}{a^4} = T^4$ (Radiation)

- Dark sector gapped!
- $\rho_{dark} \propto \frac{1}{a^4} \to \rho_{dark} \propto \frac{1}{a^3} = T^3$
- Radiation → **Matter**! (CFT → composite particle)

COFI: DM from Conformal Dark Sector!



[**Hong,** Kurup, Perelstein '19,
Hong, Kurup, Perelstein '22]

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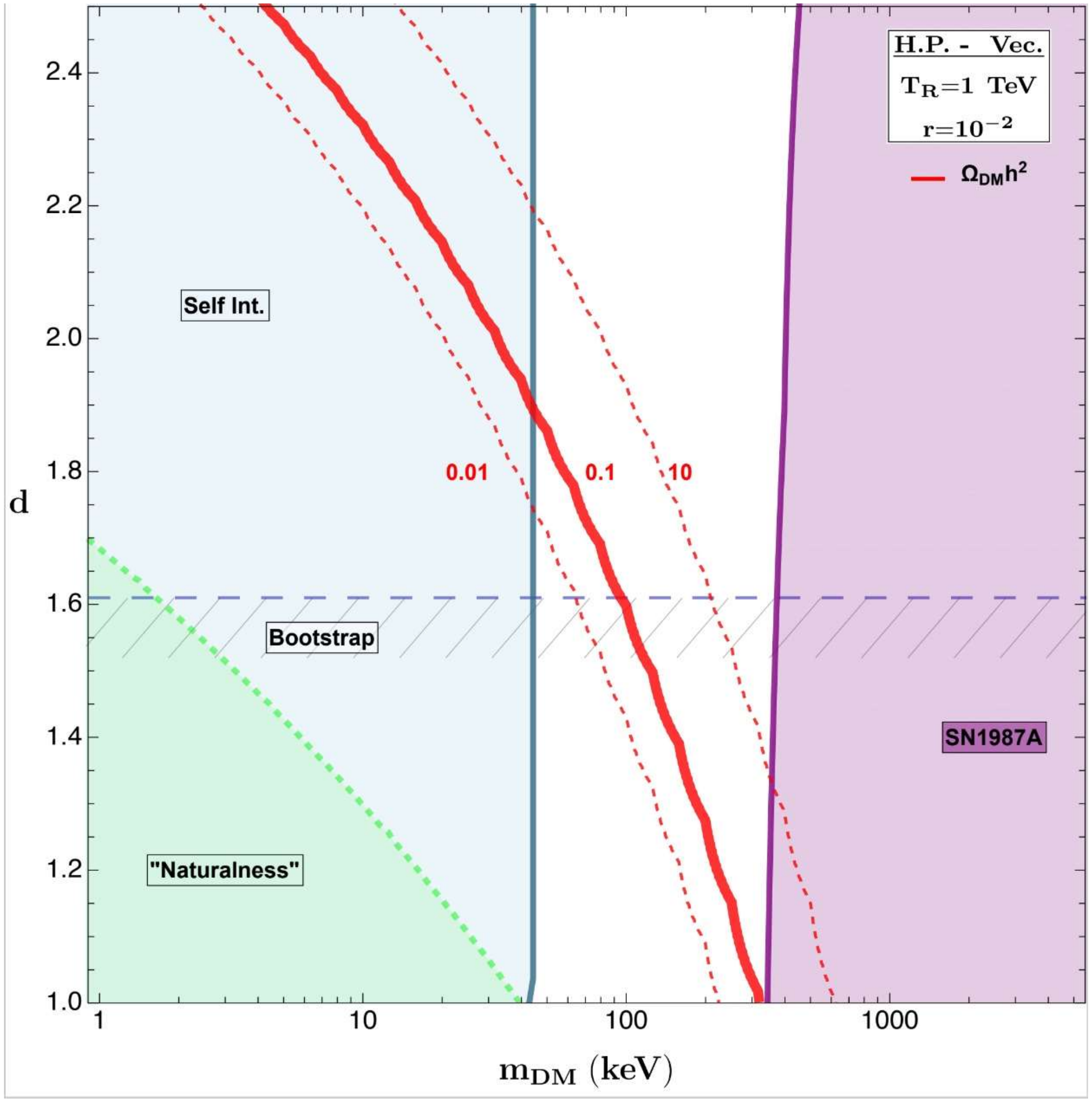

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$$\mathcal{L} \supset \lambda\, \mathcal{O}_{SM}\mathcal{O}_{CFT}$$

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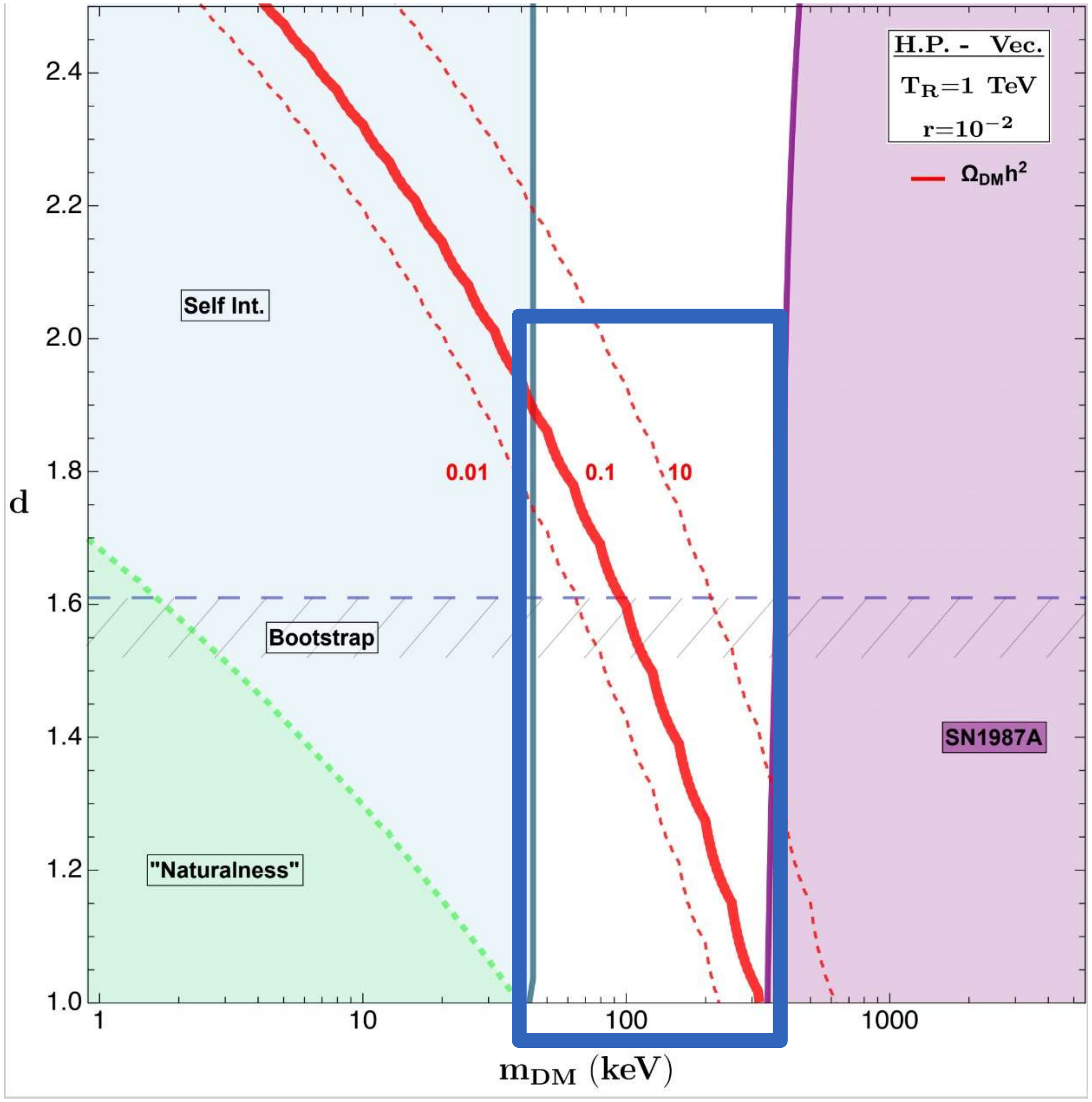

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Outline

1. Introduction to Conformal Freeze-In

2. Robustness of COFI mechanism

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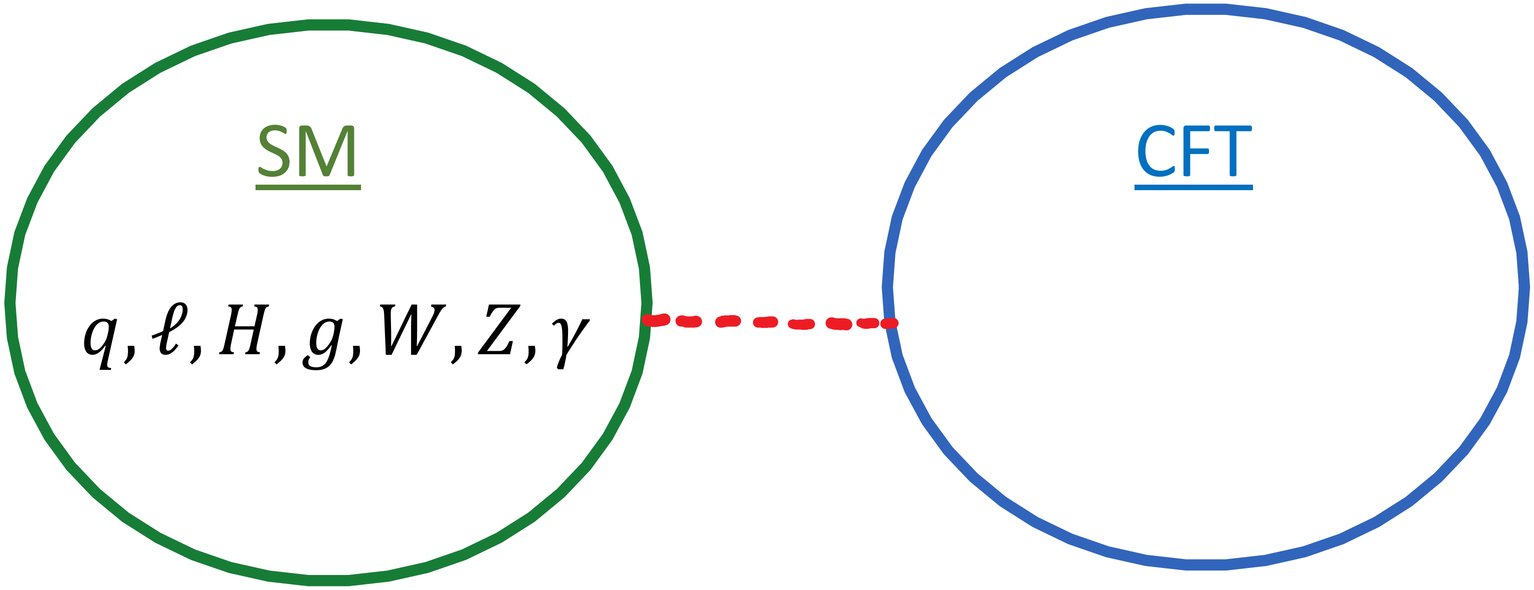
   - DM Self-Interaction, WDM, Star Cooling

4. Conclusion and Outlook

Conformal Freeze-In (COFI)



$$\mathcal{L} \supset \lambda\, \mathcal{O}_{SM} \mathcal{O}_{CFT}$$

$\mathcal{O}_{SM}$ can be classified by $(d_{SM} \leq 4)$

I. scalar $\mathcal{O}_{SM}$

(i) $\langle \mathcal{O}_{SM} \rangle \neq 0$: $H^+H,\ \ H\,\bar{Q}q,\ \ G_{\mu\nu}G^{\mu\nu}$

(ii) $\langle \mathcal{O}_{SM} \rangle = 0$: $H\,\bar{L}\ell,\ B_{\mu\nu}B^{\mu\nu}\ ,\ W_{\mu\nu}W^{\mu\nu}$

II. tensor $\mathcal{O}_{SM}$: $B_{\mu\nu}\ ,\ HL$

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II. tensor $\mathcal{O}_{SM}$: $B_{\mu\nu}$, HL "Operator Product Expansion"

Consider $\mathcal{O}_{SM} = H\,\bar{L}\ell$

Recall this represents the case: $\langle \mathcal{O}_{SM} \rangle = 0$

At $v < E < \Lambda$ we have

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^d} H\,\bar{L}\,\ell\,\mathcal{O}$$

(Q) How does Conformality-lost (m_g generation) occur?

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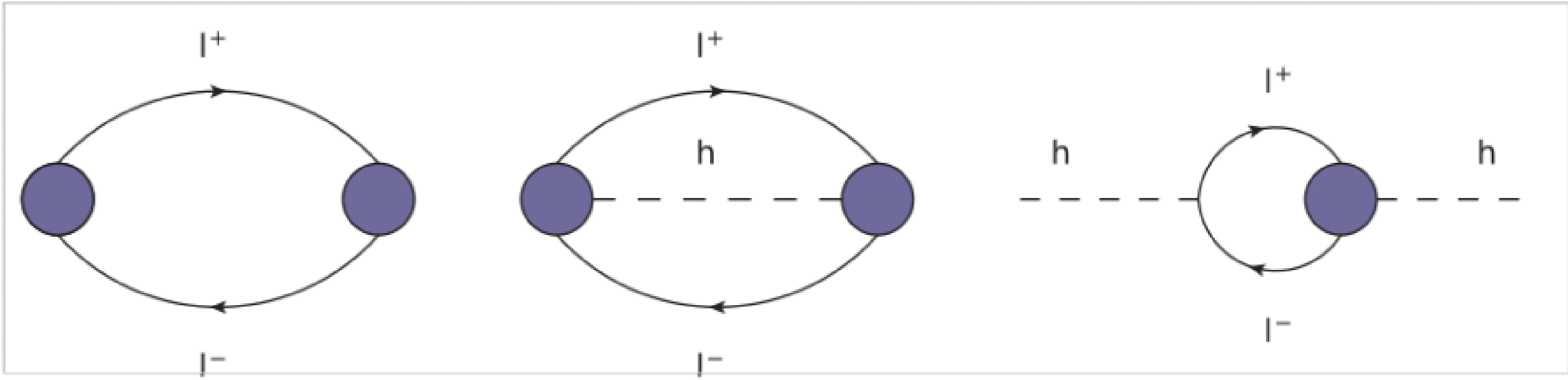
(Q) How does Conformality-lost (m_g generation) occur?

(A) "Operator Mixing Effect"

- Other operators are induced at tree or loop level



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"Operator Mixing Effect"

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^d}\frac{y_\ell\,\Lambda_{SM}^2}{16\pi^2}\, H^+ H\,\mathcal{O}$$

- This is just another kind of Higgs-portal
  (as far as breaking of CFT is concerned vs production)

Consider $\mathcal{O}_{SM} = H\,\bar{L}\ell$

At $E < v$ we have

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^d} \frac{y_\ell\, \Lambda_{SM}^2}{16\pi^2}\; H^+ H\, \mathcal{O} \;\; \rightarrow \;\; \frac{\lambda}{\Lambda^d} \frac{y_\ell\, \Lambda_{SM}^2}{16\pi^2}\; v^2\, \mathcal{O}$$

- Again, EWPT induces a scalar deformation to CFT
- CFT starts RG-running

$$m_g \;\sim \left(\frac{\lambda}{\Lambda^d} \frac{y_\ell\, \Lambda_{SM}^2}{16\pi^2}\; v^2 \right)^{1/(4-d)}$$

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"tree-level" $H^+H\,\mathcal{O} \rightarrow v^2\mathcal{O}$

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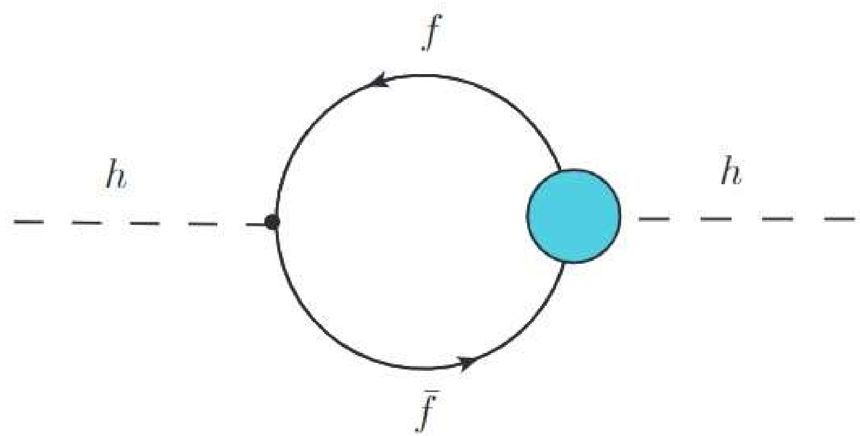
"radiative mixing"



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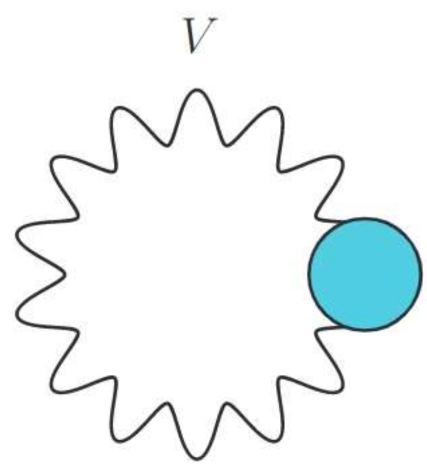
"radiative direct"



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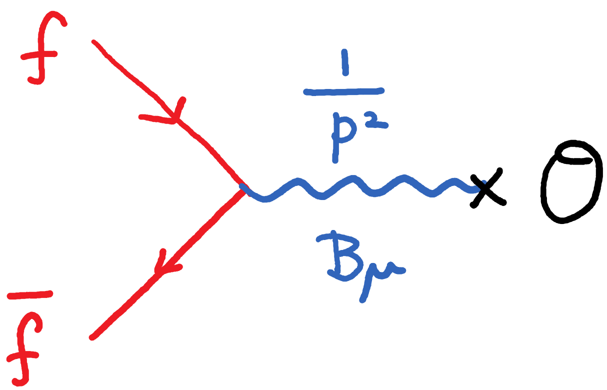
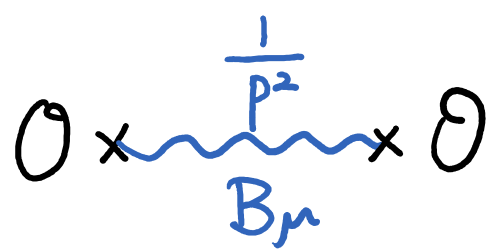
$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

At $v < E < \Lambda$ we have

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{d-2}} B_{\mu\nu}\, \mathcal{O}^{\mu\nu}$$

- At this scale, there is no local operator induced by OME





$$\mathcal{L} \propto \bar{f}\, \sigma_{\mu\nu} f\, \mathcal{O}^{\mu\nu}$$

$$\mathcal{L} \propto \mathcal{O}_{\mu\nu}\, \mathcal{O}^{\mu\nu}$$

$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

At E < v we have

$$B_\mu = \cos\theta_w \ \gamma_\mu + \sin\theta_w \ Z_\mu$$

- Now, exchange of massive Z boson can generate a local operator by **OPE** for $E \ll M_z$:

$$\mathcal{L} \sim \left(\frac{\lambda}{\Lambda^{d-2}}\right)^2 \frac{e_s \sin^2\theta_w}{M_z^{d_s-2d}} \mathcal{O}_s \,, \qquad \mathcal{O}_{\mu\nu} \times \mathcal{O}^{\mu\nu} \sim e_s \mathcal{O}_s$$

- if $d_s < 4$ this can result in a mass scale generation

$$m_g \sim \left(\left(\frac{\lambda}{\Lambda^{d-2}}\right)^2 \frac{e_s \sin^2\theta_w}{M_z^{d_s-2d}}\right)^{1/(4-d)}$$

$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

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- if d_s < *4* this can result in a mass scale generation

- currently, no numerical CFT-bootstrap bound exists.

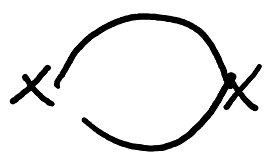
$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

Emergent composite dark photon:

$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{d-2}} B_{\mu\nu}\, \mathcal{O}^{\mu\nu}$$

- At m_g, CFT confines and

$$\mathcal{O}^{\mu\nu} \sim \frac{m_g^{d-2}}{g_\star} \rho^{\mu\nu}, \qquad \rho^{\mu\nu} = \partial^\mu \rho^\nu - \partial^\nu \rho^\mu$$

$\langle \mathcal{O}\, \mathcal{O} \rangle \sim$  $\sim \dfrac{N}{16\pi^2} \sim \dfrac{1}{g_*^2}$

$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

Emergent composite dark photon:

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- So, in the IR, we have

$$\mathcal{L} \sim \frac{\lambda}{g_\star}\left(\frac{m_g}{\Lambda}\right)^{d-2} B_{\mu\nu}\, \rho^{\mu\nu}\,, \qquad \epsilon \sim \frac{\lambda}{g_\star}\left(\frac{m_g}{\Lambda}\right)^{d-2} \ll 1$$

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Emergent composite dark photon:

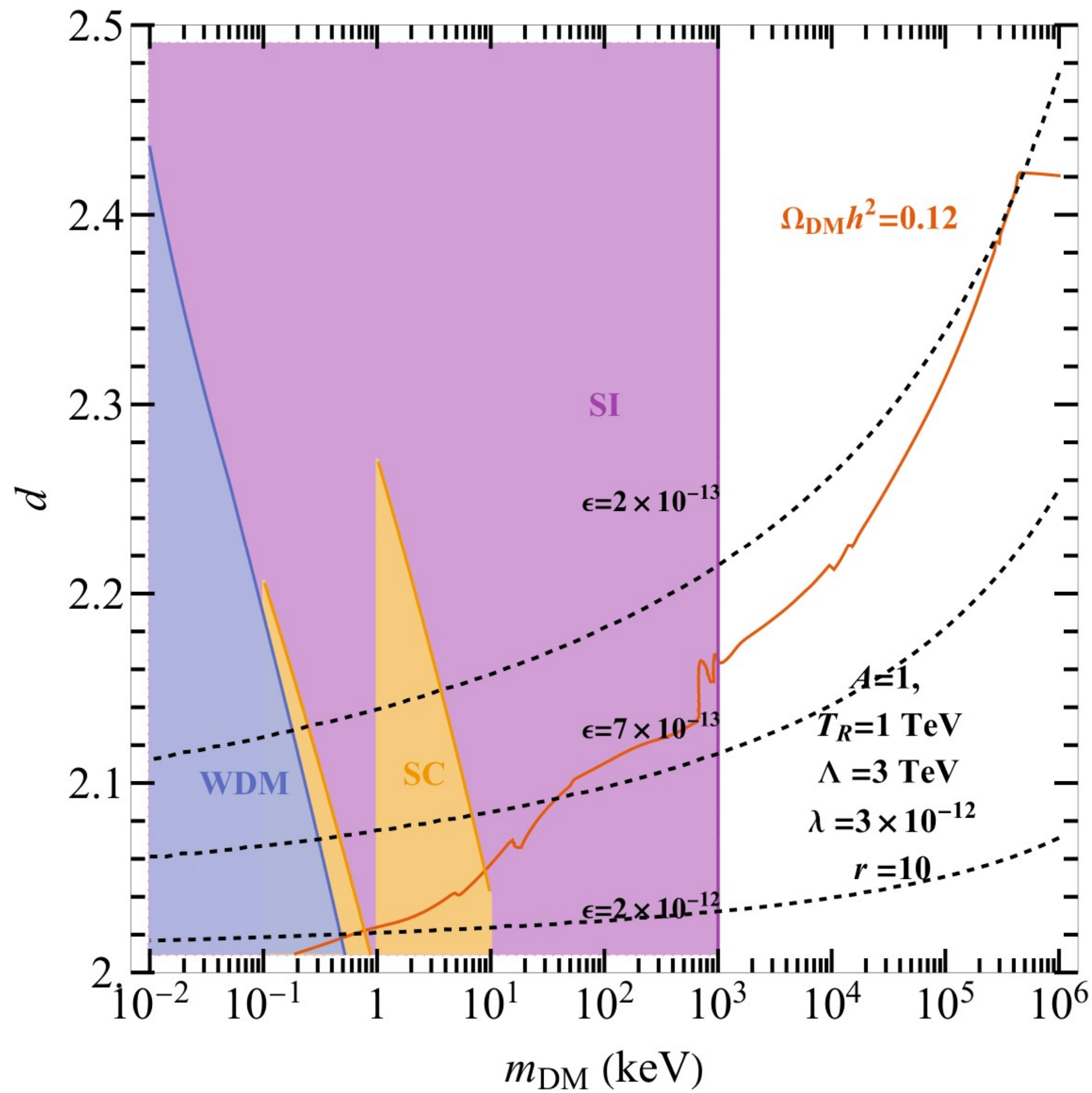
$$\mathcal{L} \sim \frac{\lambda}{\Lambda^{d-2}} B_{\mu\nu}\, \mathcal{O}^{\mu\nu} \;\rightarrow\; \epsilon\, B_{\mu\nu}\, \rho^{\mu\nu}\,, \qquad \epsilon \sim \frac{\lambda}{g_\star}\left(\frac{m_g}{\Lambda}\right)^{d-2} \ll 1$$

- $\left(\frac{\lambda}{\Lambda^{d-2}}\right)$ controls COFI production
- It also partly determines m_g via OPE
- So up to $g_\star \sim \mathcal{O}$ *(1),* the kinetic mixing ϵ fixed by othese data

smaller $\left(\frac{\lambda}{\Lambda^{d-2}}\right)$ → smaller CFT breaking → smaller m_g, ϵ

$\mathcal{O}_{SM} = B_{\mu\nu}$ (tensor operator)

IR-dominant *($d \leq 2.5$)*



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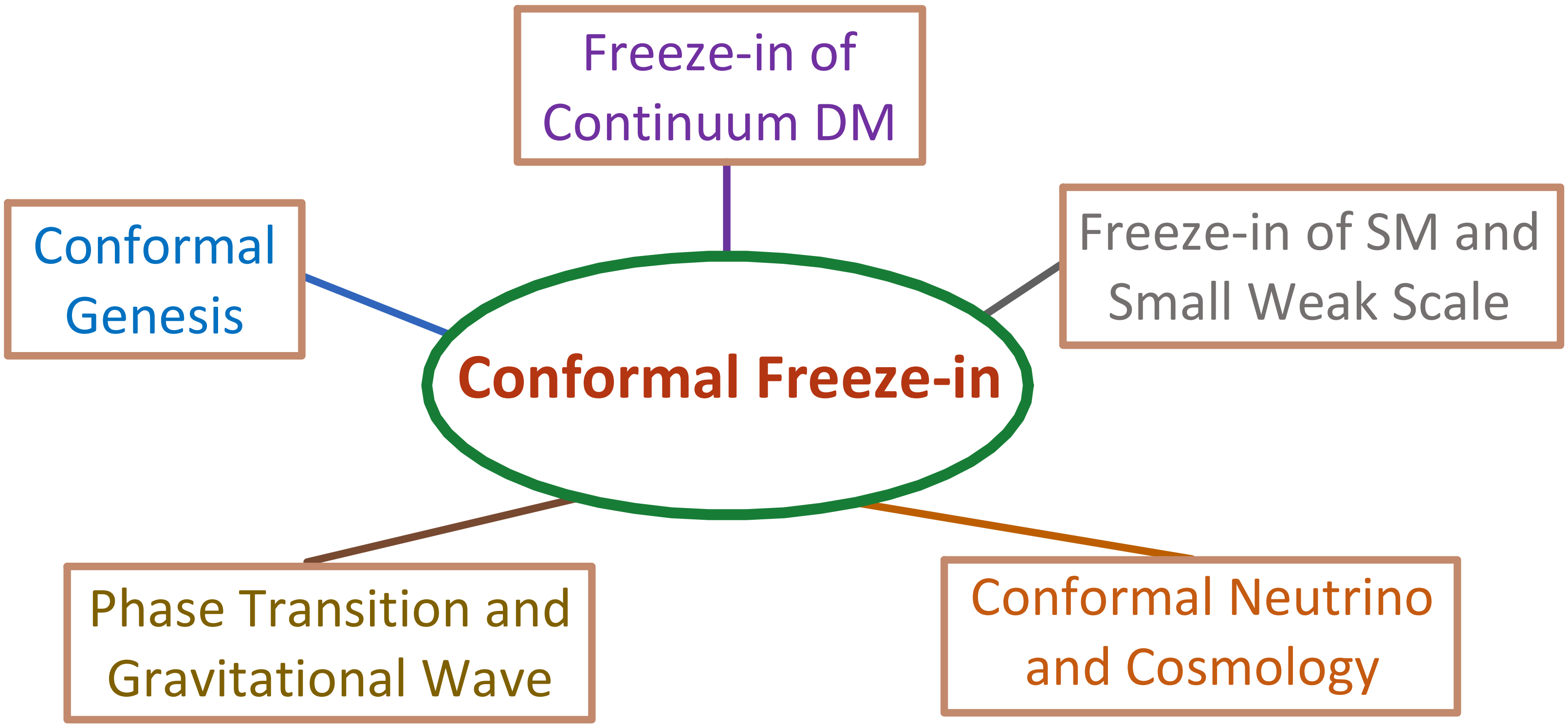
Conformal Freeze-In Physics!



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COFI Phenomenology

A general remark:

Freeze-in $\rightarrow$ weak coupling

E.g. $$\mathcal{L} \sim \frac{\lambda}{\Lambda^{d-2}} H^{+} H \, \mathcal{O} \quad \Rightarrow \quad g_{eff} \sim \left(\frac{\lambda v}{\Lambda}\right)^{d-2} \ll 1$$

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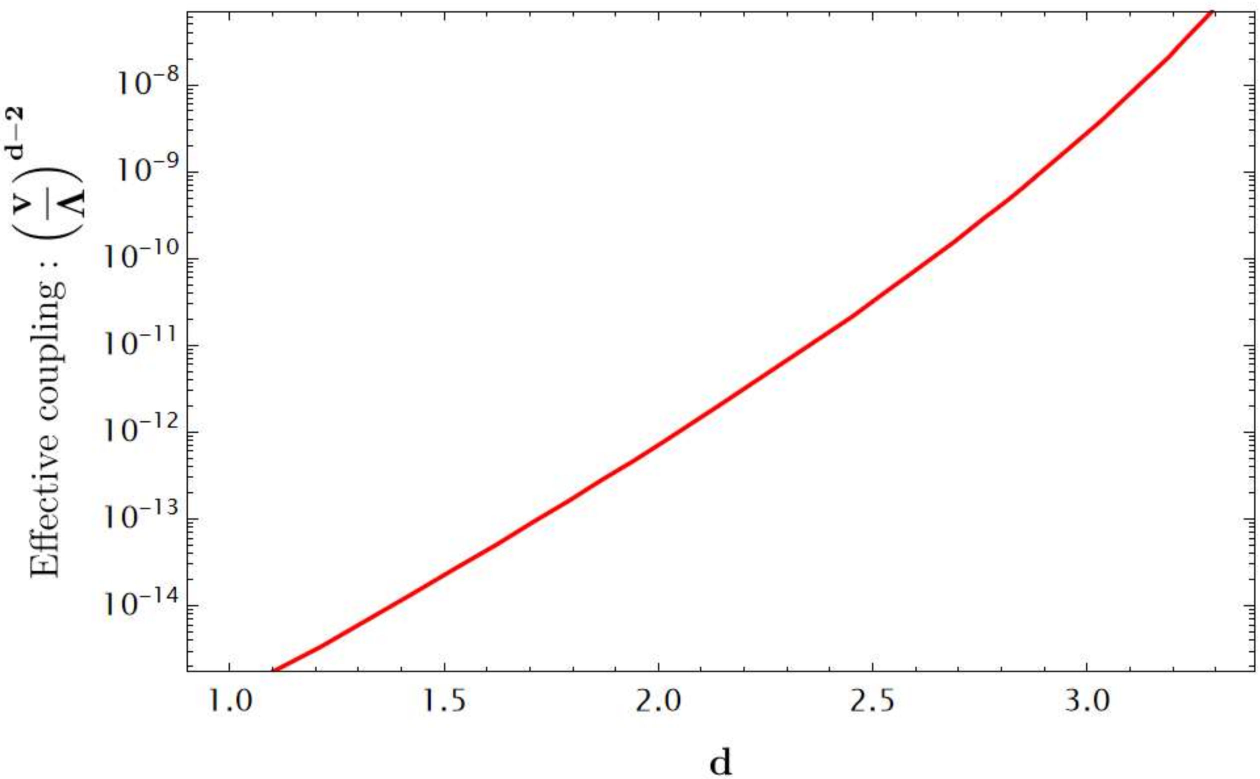


COFI Phenomenology

A general remark:

Freeze-in → weak coupling

COFI is not very much visible at:

Colliders, Rare meson decays, CMB, BBN, …

*This is a general feature of most of freeze-in models

(Q) model building question: can there be COFI with light mediator (=kinematic enhancement) ?

COFI Phenomenology

(1) DM Self-interaction

- Observation of Bullet-cluster imposes

$$\frac{\sigma_{SI}}{m_{DM}} \leq 4500\ \ GeV^{-3} \sim \frac{1}{(100\ MeV)^3}$$

COFI Phenomenology

(1) DM Self-interaction

- Observation of Bullet-cluster imposes

$$\frac{\sigma_{SI}}{m_{DM}} \leq 4500 \;\; GeV^{-3} \sim \frac{1}{(100\ MeV)^3}$$

- For a generic interacting CFT,
  we expect its hadronic IR phase is also interacting $g_\star \sim \mathcal{O}(1)$

- If DM = genuine composite hadron

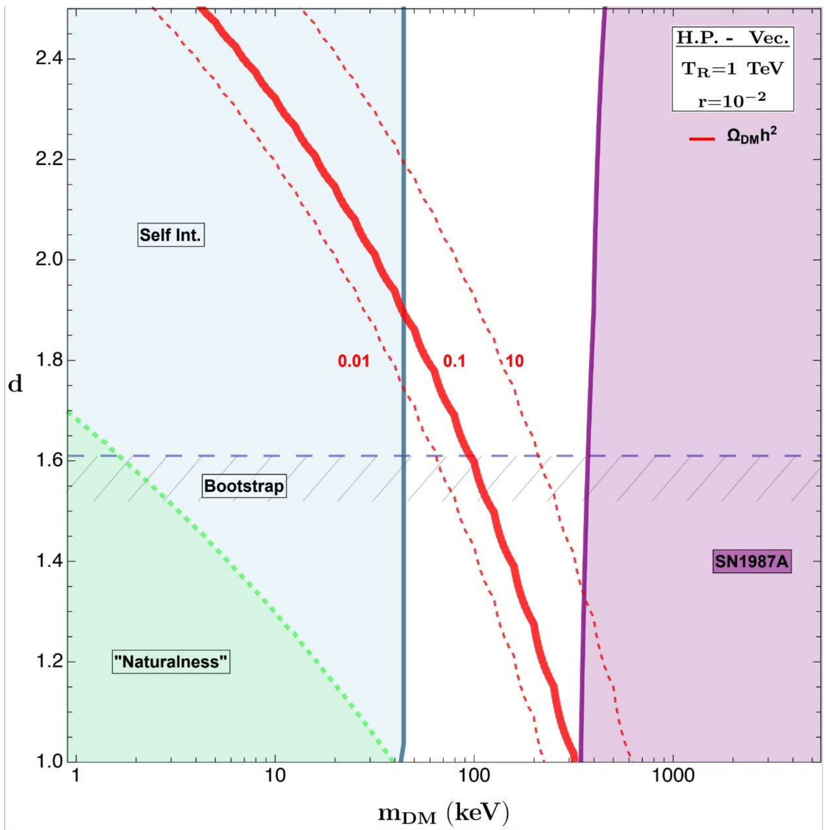
$$m_{DM} \approx m_g \,, \qquad \sigma_{SI} \sim \frac{1}{8\pi\, m_g^2} \;\; \rightarrow \;\; \frac{\sigma_{SI}}{m_{DM}} \sim \frac{1}{8\pi\, m_g^3}$$

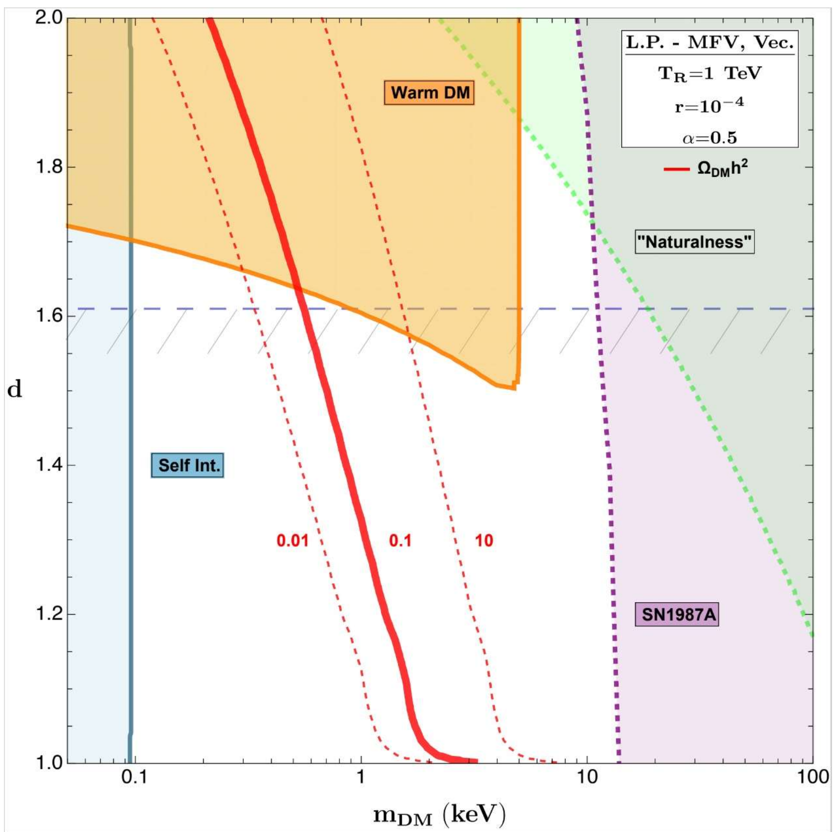
COFI Phenomenology

(1) DM Self-interaction

- In all but dark-photon-portal ($B_{\mu\nu}\mathcal{O}^{\mu\nu}$),

DM relic density $\Rightarrow$ $0.1\ keV \leq m_{DM} \leq MeV$





COFI Phenomenology

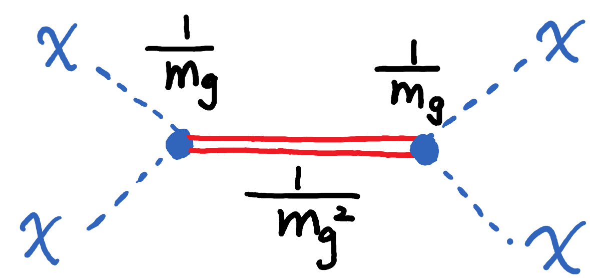
(1) DM Self-interaction

- Desired suppression of σ_{SI} possible

If DM = PNGB due to derivative suppression

(i) scalar mediator (ϕ) : $\mathcal{O}_{CFT} \sim \frac{m_g^{d-1}}{g_\star}\,\phi$

$$\mathcal{L} \sim g_\star \frac{\phi}{m_g}\,(\partial\chi)^2$$



$$\rightarrow \quad \sigma_{SI} \sim \frac{1}{8\pi}\frac{(m_{DM})^6}{m_g^8} = \frac{r^6}{8\pi\, m_g^2}\,, \qquad r = \frac{m_{DM}}{m_g} < 1$$

Typically we need : $r \sim 0.1\ - 0.01$

COFI Phenomenology

(1) DM Self-interaction

- Desired suppression of σ_{SI} possible

If DM = PNGB due to derivative suppression

(ii) vector mediator (ρ^{μ})

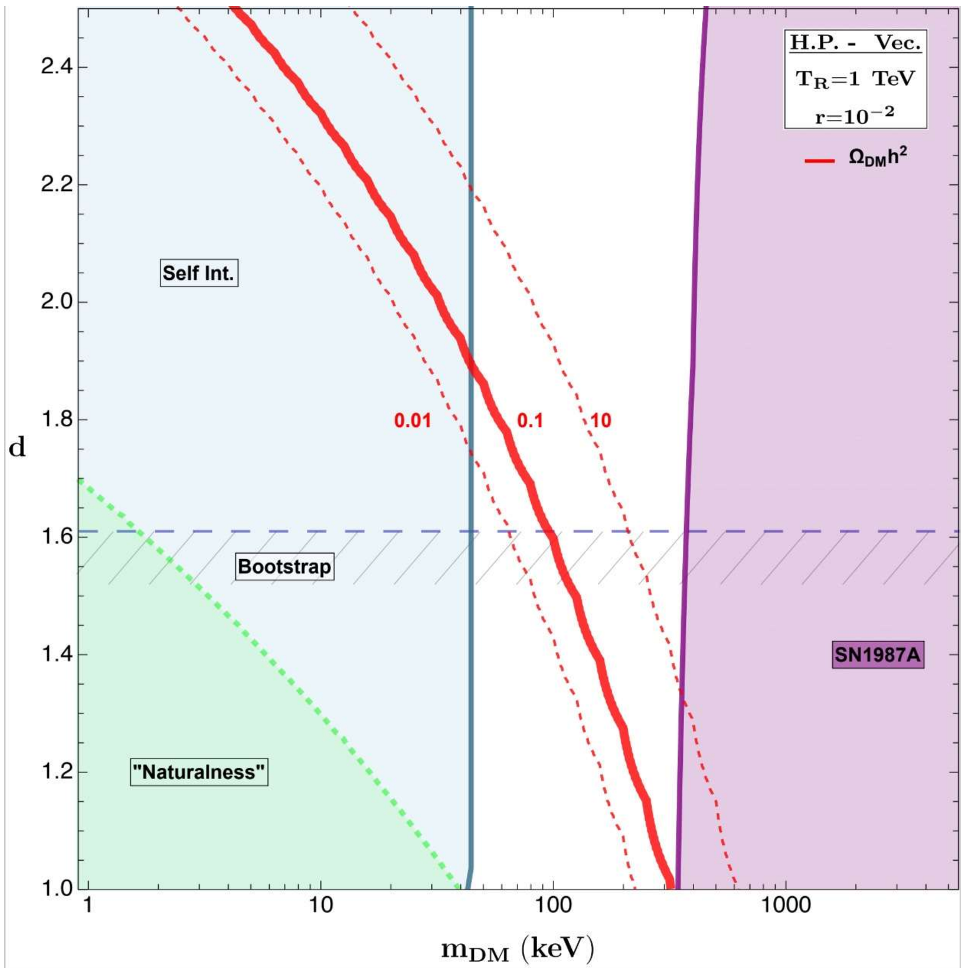
$$\mathcal{L} \sim g_{\star}\rho^{\mu}\,(\chi^{+}\partial_{\mu}\chi + h.c.)$$

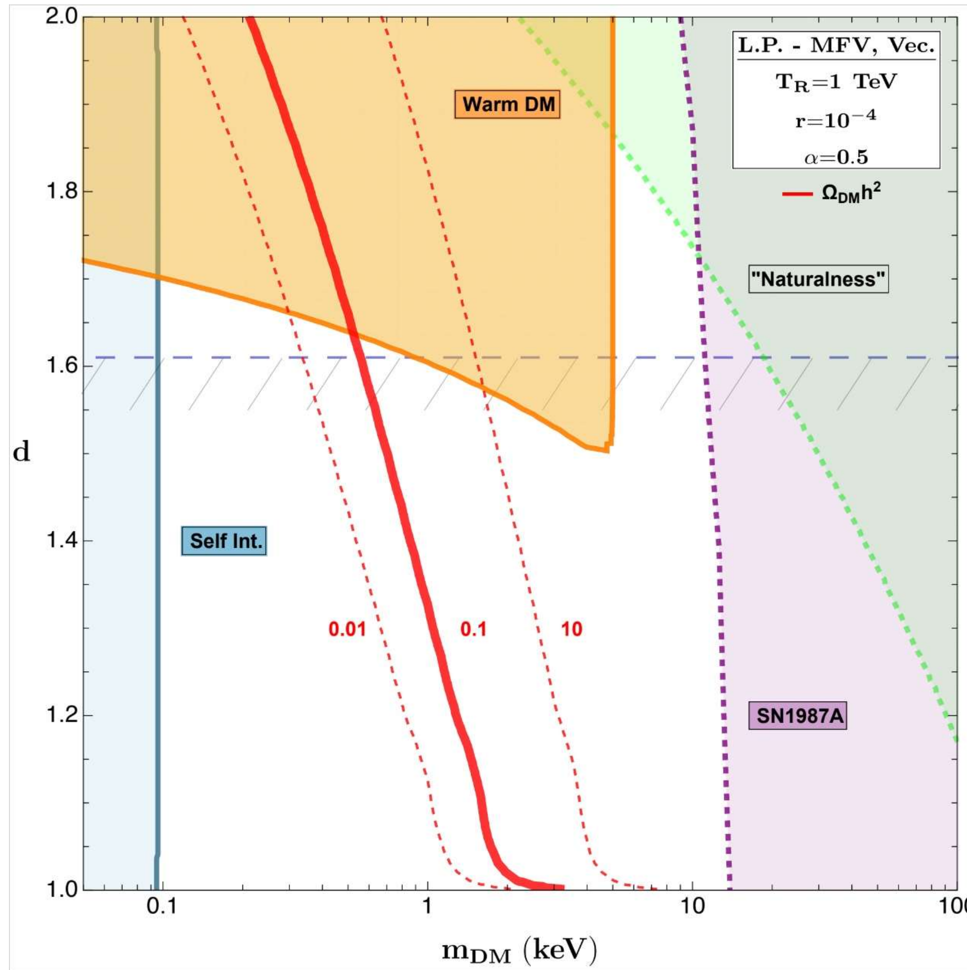
$$\rightarrow \quad \sigma_{SI} \sim \frac{1}{8\pi}\frac{(m_{DM})^2}{m_g^4} = \frac{r^2}{8\pi\, m_g^2}\,, \qquad r = \frac{m_{DM}}{m_g} < 1$$

This results in stronger bounds (but model-dependent)

COFI Phenomenology

(1) DM Self-interaction





COFI Phenomenology

(2) Warm DM bound

- If DM free-streams a comoving distance λ_{FS}
  it damps out structure below $\lambda \leq \lambda_{FS}$

- Observation of DM halo of certain size places an upper bound

$$\lambda_{FS} < \lambda_{obs}$$

- Typically, this is stated in terms of

$$\mathrm{m_{DM}} > (3.5 - 5.5)\ \mathrm{keV}$$

COFI Phenomenology

(2) Warm DM bound

- If $T_d \neq T_{SM}$ the correct form of bound is

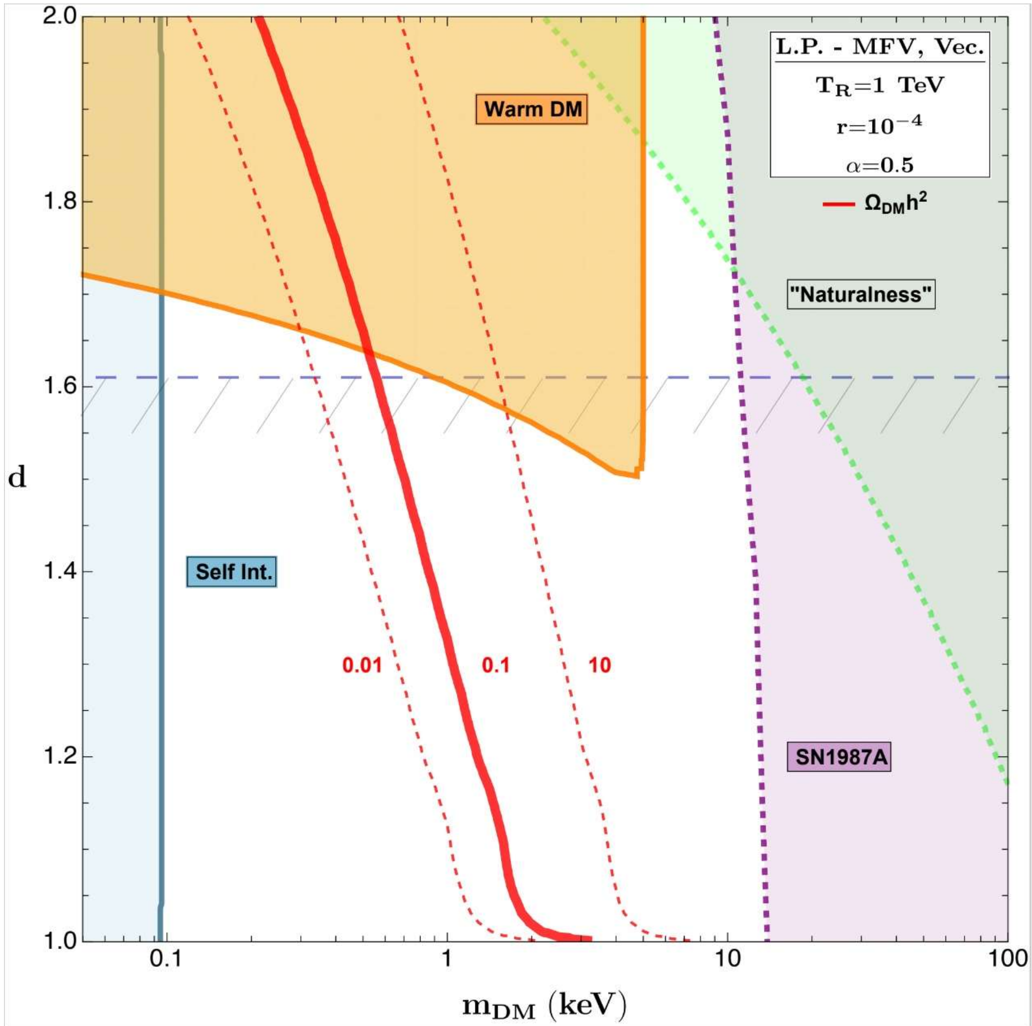
$$\lambda_{FS} \approx \frac{1}{m_{DM}} \left(\frac{T_d}{T_{SM}} \right) < \lambda_{obs}$$

- For us, $T_d \ll T_{SM}$ $\rightarrow$ bound relaxed linearly in $\frac{T_d}{T_{SM}}$

- Moreover, since $T_d\ (m_{DM}, d)$, the bound can have non-trivial "shape"

COFI Phenomenology

(2) Warm DM bound



COFI Phenomenology

(3) Stellar evolution

- Recall: COFI = light and weakly interacting DM states
- Diverse stellar systems provide non-trivial constraints

(i) Main Sequence (MS)

$T \approx 1.3\ keV, \quad \epsilon \lesssim 0.2\ erg\ g^{-1}s^{-1},\ e^-$ not degenerate

(ii) Horizontal Branch (HB)

$T \approx 10\ keV, \quad \epsilon \lesssim 10\ erg\ g^{-1}s^{-1},\ e^-$ not degenerate

(iii) Red Giant Branch (RGB)

$T \approx 10\ keV, \quad \epsilon \lesssim 10\ erg\ g^{-1}s^{-1},\ e^-$ degenerate

(iv) Supernova (SN)

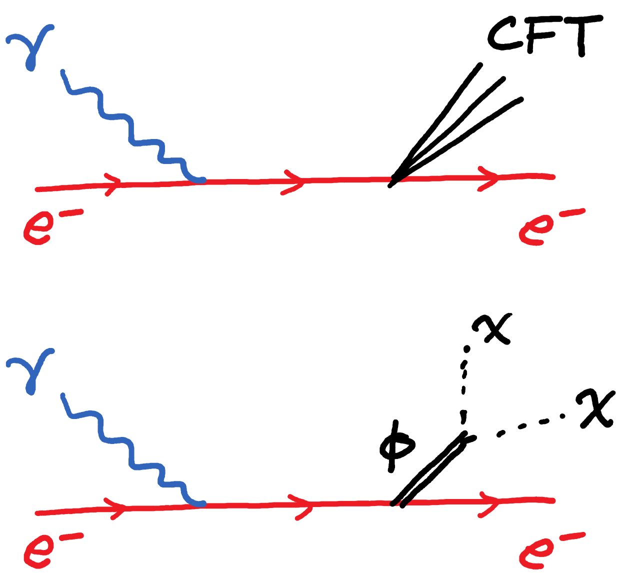
$T \sim 30\ MeV, \quad \epsilon \lesssim 10^{19}\ erg\ g^{-1}s^{-1},\ e^-, p$ degenerate

COFI Phenomenology

(3) Stellar evolution

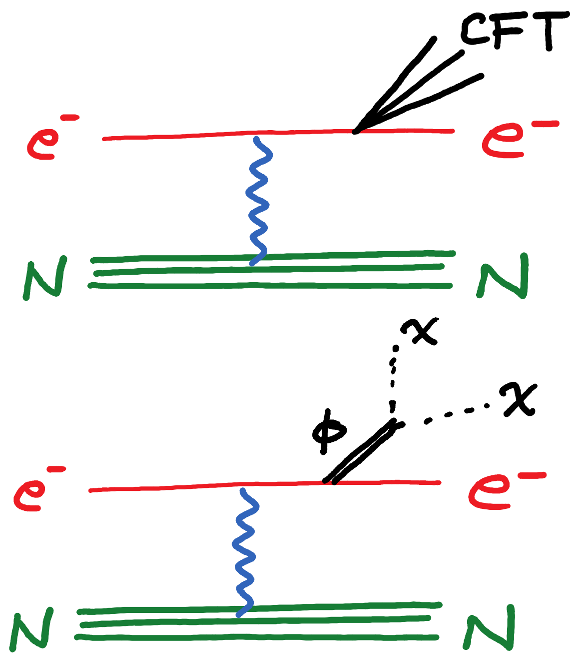
E.g. $\mathcal{O}_{SM} = H\,\bar{L}\ell$

<u>MS and HB</u>



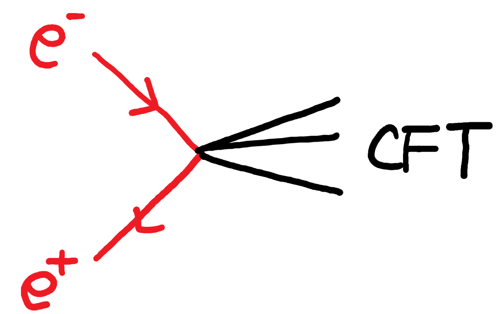
Compton

<u>RGB</u>



Bremsstrahlung

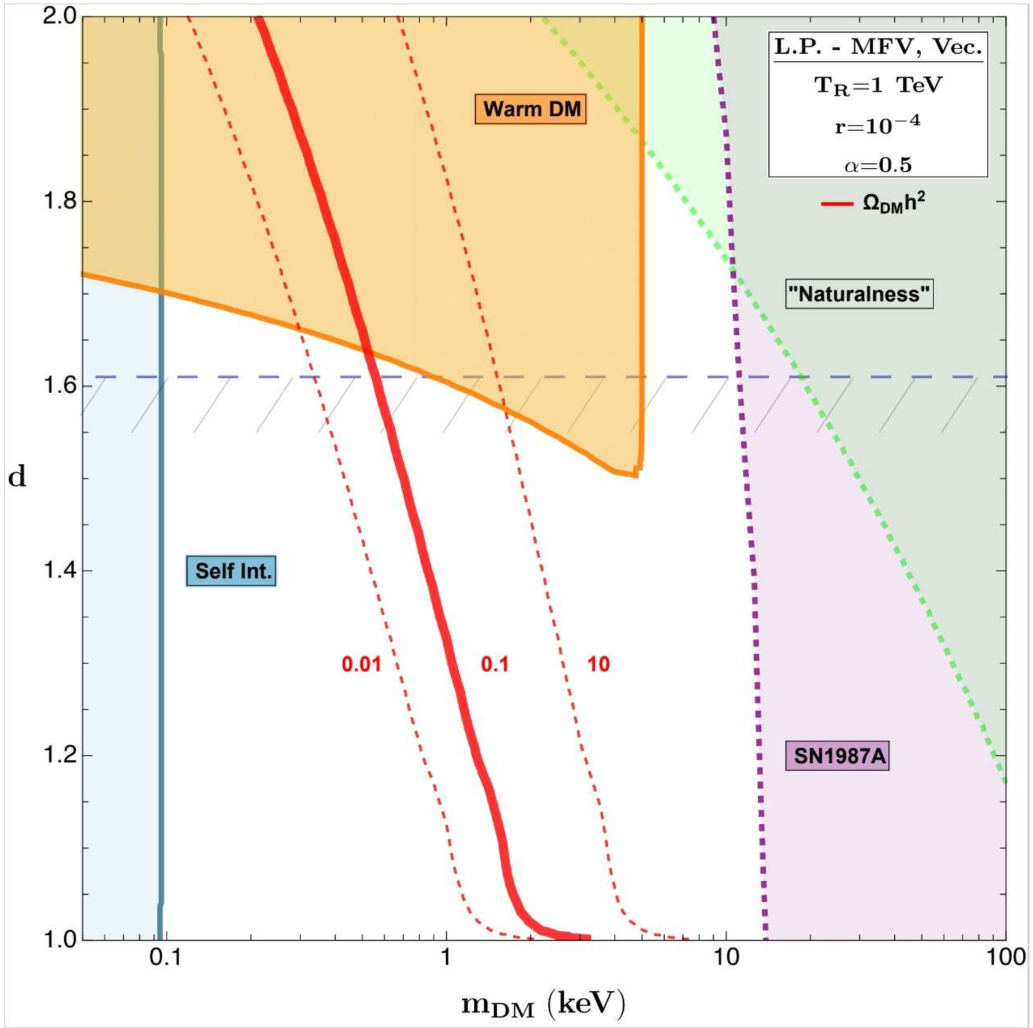
<u>SN</u>



Pair annihilation

COFI Phenomenology

(3) Stellar evolution



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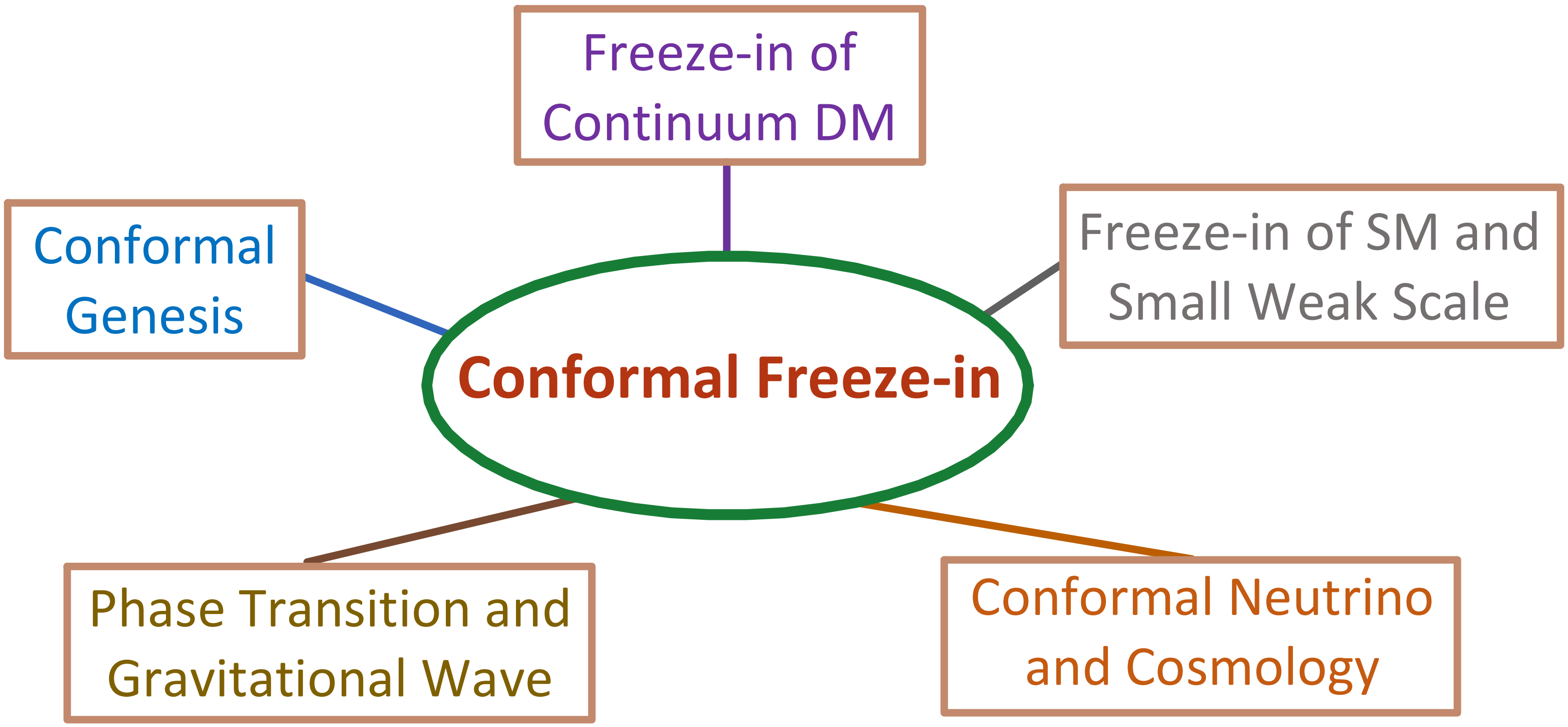

Thank you!

App-1. Why COFI?

(Q) Imagine there is a sector of CFT.

Under what conditions can this "conformal dark sector" turn into a "dark matter sector" ?

(A) Most likely* answer: Conformal Freeze-In (COFI)

(i) CFT = no massless = "radiation"

→ so for DM, we need to break the conformal invariance

→ We do it by coupling CFT to SM

$$\mathcal{L} \sim \mathcal{O}_{SM}\, \mathcal{O}_{CFT}$$

→ In fact, it is technically natural that this is the only CFT breaking (up to operator-mixing and OPE)

App-1. Why COFI?

(ii) If CFT thermalizes with SM and freezes-out around $T \sim m_g$

$$\rho_d\,(m_g) \sim m_g\, n_d\,, \qquad n_d \sim \frac{1}{\pi}\, g_{CFT} m_g^3$$

$$\rho_0 \approx \rho_d\,(m_g)\left(\frac{T_0}{m_g}\right)^3$$

$\rightarrow \quad \rho_0 = \rho_{0,crit} = 8 \times 10^{-47}\, h^2\ GeV^4$

$\rightarrow \quad m_g \sim \mathcal{O}(1)\, eV$: ruled out by WDM

App-1. Why COFI?

(iii) Why not just freeze-in in hadronic phase of CFT

- This will be the usual "particle" freeze-in

- However, it is mostly UV-dominant and model-dependent

- COFI, on the other hand, requires only CFT 2-point function

→ COFI production is independent of details of CFT
i.e. universal!

App-1. Why COFI?

(iv) Something in between?

- This would need to include important effects of $CFT \to SM$

- "Hot" CFT is an interesting but challenging topic
  : currently getting developed

- Maybe AdS/CFT helps : finite T CFT $\leftrightarrow$ AdS with BH

App-2. Small λ from UV Banks-Zaks Phase

I. At $v < \Lambda < E < M$

$$\mathcal{L} \sim \frac{\lambda_0}{M^{D_0-4}} \mathcal{O}_{SM}\, \mathcal{O}_{BZ}, \qquad\qquad D_0 = d_{SM} + d_{BZ}$$

- "BZ" = gauge theory with (strongly) interacting IR-fixed point
- $\lambda_0 \sim \mathcal{O}\,(1)\,, \quad M < M_p$
- $\mathcal{O}_{BZ} = \bar{Q}Q,\ V^a_{\mu\nu}V^{a\mu\nu}\,, \ldots.$

App-2. Small λ from UV Banks-Zaks Phase

I. At $v < \Lambda < E < M$

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II. At $E \to \Lambda$ (slow RG-"walking")

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$$\lambda = \lambda_0 \left(\frac{\Lambda}{M}\right)^{D_0-4} \ll 1$$