

# Scale Invariant FIMP Miracle

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with

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*arxiv: 2109.03259*



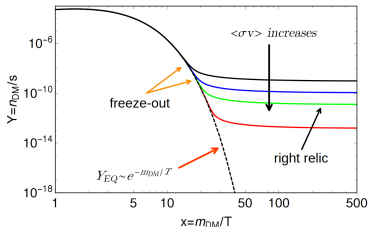
El conocimiento  
es de todos

Mincincias

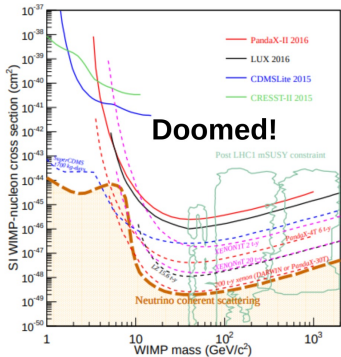
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# The 'fall' of WIMP



- DM in thermal equilibrium with SM at  $T \gg m_{DM}$ .
- Before  $n_{DM} \rightarrow 0$ , DM is rescued by 'freeze-out'  $\Gamma < H$ .
- $\rho_{DM} \sim a^{-3}$ , eventually dominating over radiation.
- WIMP miracle  $\rightarrow \langle\sigma v\rangle \sim$  weak int.



- Canonical WIMP scenario is getting cornered by DD.
- A possible alternative: avoid thermal eq. with extremely tiny DM-SM coupling  $\rightarrow$  **Freeze-in** (UV/IR).
- Tiny coupling  $\rightarrow$  very challenging to test.
- Typical signatures: particles with macroscopic lifetime/mediators.
- Coupling responsible for freeze-in does not appear in experiments.

## Scale invariance: prelude

- Massless scalar QED
- No explicit mass scale:  $V_{\text{cl}} = \frac{\lambda_\phi}{4!} |\phi|^4 \implies m_\phi^2 = \left. \frac{d^2V}{d\phi^2} \right|_{\phi=0} = 0$
- Add 1-loop correction (Coleman & E. Weinberg, PRD(1973)):

$$V = V_{\text{cl}} + V_{1\text{-loop}} \simeq \frac{\lambda_\phi}{4!} |\phi|^4 + \frac{3g_\phi^4}{64\pi^2} |\phi|^4 \left[ \log \left( \frac{|\phi|^2}{|\langle\phi\rangle|^2} \right) - \frac{25}{6} \right]$$

- $\langle\phi\rangle$  is determined by the coupling renorm. condition  $\partial_\phi V = 0$
- scalar mass:  $m_\phi^2 = \left. \frac{d^2V}{d\phi^2} \right|_{\phi=0} = \frac{3g_\phi^4}{8\pi^2} |\langle\phi\rangle|^2$
- A massive vector:  $m_X^2 = g_\phi^2 |\langle\phi\rangle|^2 \implies m_\phi^2 = \frac{3g_\phi^2}{8\pi^2} m_X^2 \ll m_X^2$

*Starting from a theory with no input mass scale, generate mass radiatively!*

## Scale invariance: prelude

Leading order RGE for  $g_\phi$ :

$$\begin{aligned}(4\pi)^2 \frac{dg_\phi(t)}{dt} &= \frac{1}{3} g_\phi(t)^3 \\ \implies \langle |\phi| \rangle &= \exp \left\{ -24\pi^2 \left[ \frac{1}{g_\phi(\langle |\phi| \rangle)^2} - \frac{1}{g_\phi(\mu_{UV})^2} \right] \right\} \mu_{UV} \\ &\simeq \mu_{UV} \exp \left[ -\frac{24\pi^2}{g_\phi(\langle |\phi| \rangle)^2} \right]\end{aligned}$$

- $\langle \phi \rangle$  is generated at a scale exponentially smaller than cut-off

*can naturally explain the smallness of the EW scale compared to the UV cutoff scale!*

## Dark sector & scale invariance

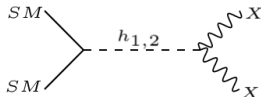
- If  $\phi$  is Higgs, then  $m_{\text{Higgs}} \ll m_{W,Z} \rightarrow$  not possible
- Apply CW in hidden sector & transmit  $\langle \phi \rangle$  to SM via portal
- Triggers the appearance of Higgs VEV:  $-\mu_{\text{SM}}^2 = \lambda_{\text{portal}} \langle \phi \rangle^2$
- Again  $\langle H \rangle \ll \langle \phi \rangle$

$$\sqrt{\frac{\lambda_H}{\lambda_{\text{portal}}}} \langle H \rangle = \langle \phi \rangle \simeq \mu_{\text{UV}} \exp[-...] \ll \mu_{\text{UV}}$$

*Dynamical generation of EW and DM scale*

- WIMP: 1306.2329, 1308.0295, 1805.01473, 1901.04168...

# Scale invariant FIMP DM



- Vector boson as FIMP DM (Bohdan et.al.1710.00320)

$$SM \times U(1)_X \times Z_2 \mid X_\mu \rightarrow -X_\mu; S \rightarrow S^*$$

- $V(H, S)_{\text{cl}} = \lambda_H (H^\dagger H)^2 + \lambda_S |S|^4 - \lambda_{HS} (H^\dagger H) |S|^2$
- Small  $g_X$  to ensure freeze-in
- 1-loop (Gildener & S.Weinberg, PRD(1976)):  $V_{\text{eff}}^{1\text{-loop}} = \alpha h_2^4 + \beta h_2^4 \log \frac{h_2^2}{\mu^2}$
- $m_2^2 = \left. \frac{d^2 V_{\text{eff}}^{1\text{-loop}}}{dh_2^2} \right|_v = \frac{1}{8\pi^2(v_h^2 + v_s^2)} \left( m_h^4 + 6m_W^4 + 3m_Z^4 + 3m_X^4 - 12m_t^4 \right)$
- DM mass:  $\frac{m_X}{1 \text{ GeV}} = \frac{g_X}{10^{-5}} \frac{v_s}{10^5 \text{ GeV}} \implies v_s \gg v_h$
- $m_2 \sim \text{MeV}$  for  $m_X \sim \text{GeV}$

*A naturally light scalar mediator!*

## Consequences of scale inv.

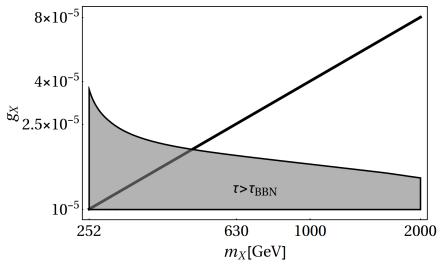
- Only two free parameters:  $m_X, g_X$
- $m_2^2 > 0$  if  $m_X \gtrsim 240 \text{ GeV} \implies$  ~~production from decay~~
- $m_2 \sim \text{MeV} \implies$  direct search possibilities
- All relevant parameters are functions of  $g_X, m_X$

$$\lambda_{H,S,HS}; \sin \theta; m_2 \sim f(g_X, m_X, v_{\text{EW}}, m_h)$$

- Decaying light scalar: BBN ( $\tau < 1 \text{ sec}$ )
- The freeze-in coupling is *directly* involved everywhere

*Light dark sector with small mixing: intensity frontier expts.*

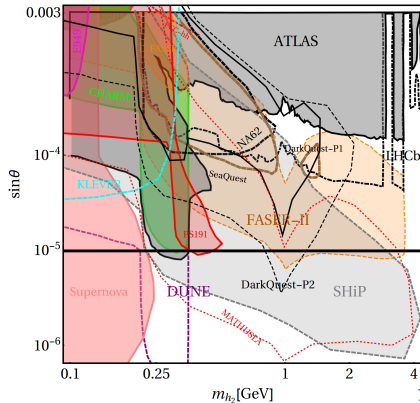
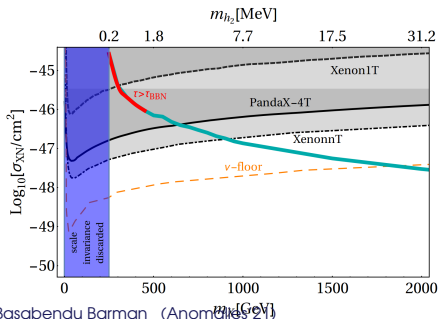
# The serendipitous FIMP



$$\Omega_X h^2 \propto (g_X/m_X)^4$$

$$\Rightarrow \sin \theta \sim 10^{-5}$$

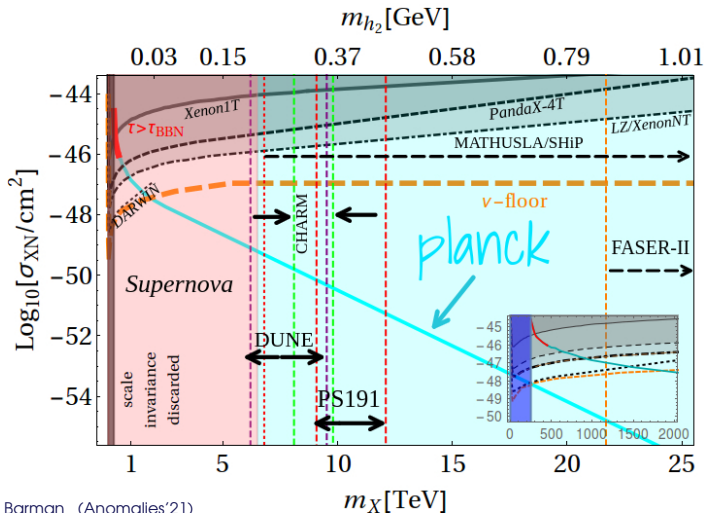
"Scale inv. FIMP miracle!"





# Summary plot

Complementarity between DD and intensity frontier



## Conclusion

- Classical scale invariance offers minimal free parameters.
- Scale invariance determines the scalar mixing uniquely.
- Naturally light scalar facilitates experimental verification.
- Freeze-in coupling controls EVERYTHING.
- *Testing SI-FIMP miracle with different portals?*

## Conclusion

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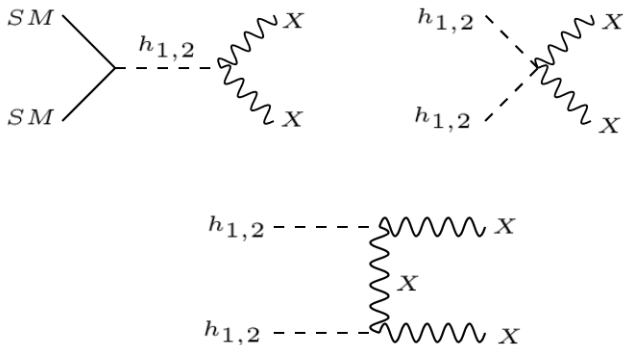
Thank you for your attention!

**#StandWithFarmers**

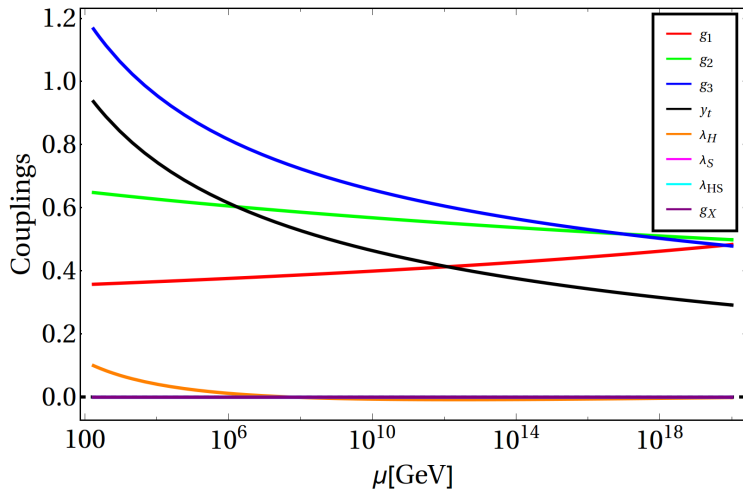
# Backup Slides

# Production channels

Only  $2 \rightarrow 2$  scattering processes



## RG running



## Dimensional transmutation

*trading a dimensionless parameter with a dimensionful one*

Scalar QED:  $g_\phi, \lambda_\phi \rightarrow g_\phi, \langle \phi \rangle$

$$\lambda(|\langle \phi \rangle|) = \frac{33}{8\pi^2} g_\phi^4(|\langle \phi \rangle|)$$

SM+ $U(1)_X$ : holds as well!

$$\lambda(|\langle \phi \rangle|) - \frac{33}{8\pi^2} g_\phi^4(|\langle \phi \rangle|) - \underbrace{12 \frac{\lambda_{HS}(|\langle \phi \rangle|)^2}{\lambda_H(|\langle \phi \rangle|)}}_{\text{small deformation}} = 0$$

# Cross-sections

$$\sigma(s)_{\ell\ell\rightarrow XX} \simeq \frac{g_X^4 m_\ell^2}{64\pi s} \frac{\sqrt{(s-4m_X^2)(s-4m_\ell^2)}}{(s-m_{h_1}^2)^2 + \Gamma_{h_1}^2 m_{h_1}^2} \left(\frac{m_{h_1}^2 - m_{h_2}^2}{s-m_{h_2}^2}\right)^2 \left(\frac{s^2 - 4m_X^2 s + 12m_X^4}{(m_X^2 + g_X^2 v_h^2)^2}\right)$$

$$\sigma(s)_{qq\rightarrow XX} \simeq \frac{g_X^4 m_q^2}{192\pi s} \frac{\sqrt{(s-4m_X^2)(s-4m_q^2)}}{(s-m_{h_1}^2)^2 + \Gamma_{h_1}^2 m_{h_1}^2} \left(\frac{m_{h_1}^2 - m_{h_2}^2}{s-m_{h_2}^2}\right)^2 \left(\frac{s^2 - 4m_X^2 s + 12m_X^4}{(m_X^2 + g_X^2 v_h^2)^2}\right)$$

$$\sigma(s)_{VV\rightarrow XX} \simeq \frac{g_X^4}{288\pi s} \sqrt{\frac{s-4m_X^2}{s-4m_V^2}} \left(\frac{m_{h_1}^2 - m_{h_2}^2}{s-m_{h_2}^2}\right)^2 \left(\frac{1}{(s-m_{h_1}^2)^2 + \Gamma_{h_1}^2 m_{h_1}^2}\right)$$

$$\left[ \frac{(s^2 - 4m_X^2 s + 12m_X^4)(s^2 - 4m_V^2 s + 12m_V^4)}{(m_X^2 + g_X^2 v_h^2)^2} \right]$$

$$\sigma(s)_{h_1 h_1 \rightarrow XX} \simeq \frac{g_X^4}{32\pi s} \left(\frac{m_{h_1}}{m_X}\right)^4 \frac{(s+2m_{h_1}^2)^2}{(s-m_{h_1}^2)^2 + \Gamma_{h_1}^2 m_{h_1}^2} \sqrt{\frac{s-4m_X^2}{s-4m_{h_1}^2}} \left(1 - \frac{4m_X^2}{s} + \frac{12m_X^4}{s^2}\right)$$