Scale-invariant scalar field dark matter through the Higgs portal

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The Model – Higgs portal scalar field dark matter (SFDM)

• **Oscillating scalar field dark matter** (SFDM), $\Phi$, interacting with the Higgs doublet, $\mathcal{H}$, through scale-invariant interactions (arXiv:1709.09674 and arXiv:1802.09434):

$$- \mathcal{L}_{int} = - g^2 |\Phi|^2 |\mathcal{H}|^2 + \lambda_\phi |\Phi|^4 + V(\mathcal{H}) + \xi R |\Phi|^2$$

$g$ - SFDM-Higgs coupling, $\lambda_\phi$ - SFDM self-coupling, $\xi$ – non-minimal coupling (NMC), $R$ – Ricci Scalar; $\Phi = \frac{\phi}{2}$

• Our candidate: extremely small self-interactions $\Rightarrow$ oscillating scalar condensate that is never in thermal equilibrium;

• **Scale-invariance of the full theory** that is broken somehow $\Rightarrow$ negative squared mass to the Higgs $\Rightarrow$ SFDM mass;

• **U(1) gauge** symmetry, negative coupling $\Rightarrow$ Spontaneously broken; DM field may decay $\Rightarrow$ Astrophysical signatures.
Inflation and initial conditions

\[- \mathcal{L}_{\text{int}} = - g^2 |\Phi|^2 |\mathcal{H}|^2 + \lambda_\phi |\Phi|^4 + V(\mathcal{H}) + \xi R |\Phi|^2\]

- $\xi \gg g, \lambda_\phi \Rightarrow m_\phi$ is given by the NMC to the curvature scalar, $R \approx 12 H_{\text{inf}}^2(r)$.

- $H_{\text{inf}}(r) \approx 2.5 \times 10^{13} \left( \frac{r}{0.01} \right)^{1/2} \text{GeV}, r < 0.10$. [Planck Collaboration 2018].

- $m_\phi \approx \sqrt{12 \xi} H_{\text{inf}}(r) \gtrsim H_{\text{inf}}(r)$ for $\xi \gtrsim 0.1 \Rightarrow \text{No observable isocurvature modes}$ in the CMB spectrum $\Rightarrow \text{Compatible}$ with observations.
Inflation and initial conditions

- **Quantum fluctuations** for a massive field \( \frac{m_\phi}{H_{\text{inf}}} > \frac{3}{2} \):

\[
|\delta \phi_k|^2 \simeq \left( \frac{H_{\text{inf}}}{2\pi} \right)^2 \frac{H_{\text{inf}}}{m_\phi} \frac{2\pi^2}{aH_{\text{inf}}} \left( \frac{a}{H_{\text{inf}}} \right)^3
\]

Integrating over all modes

\[\langle \phi^2 \rangle \simeq \alpha^2 H_{\text{inf}}^2\]

- \( \langle \phi^2 \rangle \) sets the initial amplitude for field oscillations in the **post-inflationary era**:

\[
\phi_{\text{inf}} = \sqrt{\langle \phi^2 \rangle} \simeq \alpha H_{\text{inf}}(r) \quad \alpha \simeq 0.05 \xi^{-1/4}
\]
SFDM dynamics – Before the EWPT

- After inflation and the reheating ⇒ Radiation dominated epoch ⇒ \( R = 0 \)

\[-L_{int} = - g^2 |\Phi|^2 |\mathcal{H}|^2 + \lambda_\phi |\Phi|^4 + V(\mathcal{H}) + \xi R |\Phi|^2\]

- The field starts to oscillate at \( T_{rad} = \left( \frac{270}{\pi^2 g_*} \right)^{1/4} (\phi_{inf} M_{Pl})^{1/2} \lambda_\phi^{1/4}, \ \phi_{rad}(T) = \frac{\phi_{inf}}{T_{rad}} \ T; \)

- Since \( T \sim a^{-1}, \ \rho_\phi \sim a^{-4} \) ⇒ Field behaves like dark radiation.
SFDM dynamics – After the EWPT

- At the EWPT - still radiation era ⇒ $R = 0$

\[-\mathcal{L}_{\text{int}} = -\frac{g^2}{4}\phi^2 h^2 + \frac{\lambda\phi}{4} \phi^4 + \frac{\lambda h}{4} (h^2 - \tilde{v}^2)^2\]

Higgs vev

\[h_0 = \left(1 - \frac{g^4}{4\lambda\phi\lambda h}\right)^{-1/2} \tilde{v} \equiv v\]

$\phi$ vev

\[\phi_0 = \frac{gv}{\sqrt{2\lambda\phi}}\]

$v = 246 \text{ GeV}$
SFDM dynamics – After the EWPT

- \( T_{EW} \sim m_W \) - \( \phi \) starts to oscillate around \( \phi_0 \), with initial amplitude \( \phi_{DM} \equiv x_{DM} \phi_0 \) (\( x_{DM} \lesssim 1 \));

- Below \( T_{EW} \), \( \phi^2 \) dominates over \( \phi^4 \).

The field smoothly changes from a dark radiation to a cold dark matter behavior as the potential becomes quadratic about the minimum.
SFDM dynamics – After the EWPT

- CDM: \( \phi(T) = \phi_{DM} \left( \frac{T}{T_{EW}} \right)^{3/2} \)

\[
\frac{n\phi}{s} = \frac{\rho\phi/m\phi}{\frac{2\pi^2}{45}g_*S T^3} = \text{const}
\]

- Present DM abundance: \( \Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{\text{crit},0}} = 0.26 \)

\[
m_{\phi} = \left( 6\Omega_{\phi,0} \right)^{1/2} \left( \frac{g_*S}{g_*S_0} \right)^{1/2} \left( \frac{T_{EW}}{T_0} \right)^{3/2} \frac{H_0M_{Pl}}{\phi_{DM}}
\]

- Also \( m_{\phi} = gv \)

\[
g \approx 2 \times 10^{-3} \left( \frac{x_{DM}}{0.5} \right)^{-1/2} \lambda_{\phi}^{1/4}
\]
SFDM dynamics – Constraints

• **Idea:** $\phi$ is **never** in thermal equilibrium with the cosmic plasma;

• **Constraints** on $g$ and $\lambda_\phi$ to prevent the **condensate evaporation** (i.e., the field thermalizes and becomes a WIMP-like candidate (WIMP- Weakly Interacting Massive Particle));

\[
g < 8 \times 10^{-4} \left( \frac{g_\ast}{100} \right)^{1/8}
\]

\[
\lambda_\phi < 6 \times 10^{-10} \left( \frac{g_\ast}{100} \right)^{1/5} \left( \frac{r}{0.01} \right)^{-1/5} \xi^{1/10}
\]

This **limits** the viable DM mass range to

\[
m_\phi < 1 \text{ MeV}.
\]
SFDM phenomenology - $\phi$ decay into photons

- SFDM can decay into the same decay channels as the Higgs;

- $m_\phi < 1$ MeV $\Rightarrow$ decay into photon pairs;

\[
\tau_{\phi \rightarrow \gamma\gamma} \approx 7 \times 10^{27} \left( \frac{m_\phi}{7 \text{keV}} \right)^{-5} \left( \frac{x_{DM}}{0.5} \right)^2 \text{sec}
\]

$\tau_\phi \gg \tau_{\text{Uni}}$

Can lead to an observable monochromatic line in the spectrum of galaxies and galaxy clusters.
The 3.5 keV line

• XMM-Newton X-ray observatory discovered a 3.5 keV line in the Galactic Center, Andromeda and Perseus cluster [Bulbul et al., 2014; Boyarski et al., 2014; Cappelluti et al., 2017];

• What is producing the excess? DM decay/annihilation? Other astrophysical process – emission from Potassium? [Jeltema&Profumo, 2014]

• Controversy about the presence of the line in dwarf galaxies, such as Draco;

Decay of a DM particle with $m \approx 7$ keV and $\tau \sim (6 - 9) \times 10^{27}$ sec can explain the line observed in the Galactic Center, Andromeda and Perseus.
\[ \tau_\phi \approx 7 \times 10^{27} \left( \frac{m_\phi}{7 \text{ keV}} \right)^{-5} \left( \frac{x_{DM}}{0.5} \right)^2 \text{ sec} \]
SFDM phenomenology – Model predictions

\[ m_\phi = 7 \text{ keV} \]

\[ g \approx 3 \times 10^{-8} \]

\[ \lambda_\phi \approx 4 \times 10^{-20} \]

Satisfy the constraints on \( g \) and \( \lambda_\phi \).
### SFDM phenomenology – Model predictions

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>$r$</th>
<th>$g$</th>
<th>$\lambda_\phi$</th>
</tr>
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<tbody>
<tr>
<td>Suppresses the potential CDM isocurvature perturbations</td>
<td>Sets the amplitude field at the onset of radiation era</td>
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4/09/2018

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SFDM phenomenology – Model predictions

\begin{align*}
\xi & \quad \text{Suppresses the potential CDM isocurvature perturbations} \\
r & \quad \text{Sets the amplitude field at the onset of radiation era} \\
g & \\
\lambda_\phi
\end{align*}

- **After** the EWPT, the field oscillates about \( \phi_0 \) - only depends on \( g \) and \( \lambda_\phi \).
SFDM phenomenology – Model predictions

- Suppresses the potential CDM isocurvature perturbations
- Sets the amplitude field at the onset of radiation era

- **After** the EWPT, the field oscillates about $\phi_0$ - only depends on $g$ and $\lambda_\phi$.

- Present DM abundance, field mass and its decay – only dependent on $g$ and $\lambda_\phi$. 
SFDM phenomenology – Model predictions

Suppresses the potential CDM isocurvature perturbations

Sets the amplitude field at the onset of radiation era

- After the EWPT, the field oscillates about \( \phi_0 \) - only depends on \( g \) and \( \lambda_\phi \).

- Present DM abundance, field mass and its decay – only dependent on \( g \) and \( \lambda_\phi \).

SFDM accounts for all DM ⇒ Relation between \( g \) and \( \lambda_\phi \)
⇒ \( m_\phi \) and \( \tau_\phi \) depend on one single parameter
Conclusions

• Oscillating scalar field coupled to the Higgs is a **viable DM candidate**;

• The field behaves like **dark radiation** up to the **EWPT**, behaving like **CDM afterwards**;

• The model predicts a **3.5 keV line**, with only **one free parameter**;

Thank you for your attention!
Backup slides
SFDM phenomenology – Laboratory signatures

- \( g \) is very small \( \Rightarrow \) hard to probe in the lab;

- Higgs decays into invisibles - \( \Gamma_{h \rightarrow \phi\phi} \sim 10^{-27} \) - too small to probe in near future;

- SFDM coupling to photons - Light shining through wall experiments (but conversion probabilities are very small);

- May induce small oscillations of fundamental constants, \( m_e \) and \( \alpha \) \( \Rightarrow \) detection using interferometry.
Introduction and motivation

Why a scalar field dark matter?

• Fits:
  - evolution of cosmological densities [Matos, Vazquez-Gonzalez, Magana 2009];
  - flat central density profile of the dark matter [Matos, Nunez 2003];
  - acoustic peaks of CMB [Rodriguez-Montoya, Magana, Matos, Perez-Lorenzana 2010];
  - observed properties of dwarf galaxies [Lee, Lim 2010];

• Explains:
  - cusp and the missing satellite problems [Lee, Lim 2010; Lee 2009; Harko 2011];
  - collision of galaxy clusters (e.g., Bullet Cluster) [Lee, Lim, Choi 2008];
Previous work – Oscillating scalar field as DM candidate

- In arXiv:1603.06242 we studied an oscillating scalar field as a DM candidate, coupled to the Higgs:

\[- \mathcal{L}_{\text{int}} = g^2 |\Phi|^2 |\mathcal{H}|^2\]

- Literature: “Higgs-portal” DM models: abundance of DM is set by the decoupling and freeze-out from thermal equilibrium ⇒ $m \sim GeV - TeV$ (Weakly Interacting Massive Particles - WIMPs) [Silveira, Zee 1985; Bento, Bertolami, Rosenfeld 2001; Burgess, Pospelov, ter Veldhuis 2001];

- Our candidate: extremely small self-interactions ⇒ oscillating scalar condensate that is never in thermal equilibrium;

- It is possible to show that an oscillating scalar field is a viable DM candidate;
SFDM dynamics – Before the EWPT

• After inflation and the reheating ⇒ Radiation dominated epoch ⇒ $R = 0$

\[ -\mathcal{L}_{int} = -g^2 |\Phi|^2 |\mathcal{H}|^2 + \lambda_\phi |\Phi|^4 + V(\mathcal{H}) + \xi R |\Phi|^2 \]

• EOM: \( \ddot{\phi} + 3H \dot{\phi} + V'(\phi) = 0; \) when \( m_\phi = \sqrt{3} \frac{\lambda_\phi}{\phi} \phi > H, \) field starts to oscillate;

friction term

• The field starts to oscillate at \( T_{rad} = \left( \frac{270}{\pi^2 g_*} \right)^{1/4} \left( \phi_{inf} M_{Pl} \right)^{1/2} \lambda_\phi^{1/4}, \) with \( \phi_{rad}(T) = \frac{\phi_{inf}}{T_{rad}} T; \)

• Since \( T \sim a^{-1}, \) \( \rho_\phi \sim a^{-4} \) ⇒ Field behaves like dark radiation.
SFDM dynamics – After the EWPT

• Recall:  \( \phi_{EW} = \frac{\phi_{inf}}{T_{rad}} T_{EW} \)  \( \phi_{EW} \approx 10^{-4} g_*^{1/4} \xi^{-1/8} \left( \frac{r}{0.01} \right)^{1/4} \frac{\lambda^{1/4}}{g} \phi_0; \)

• Note:  \( g \gtrsim 10^{-4} \lambda^{1/4}_\phi, \xi \sim O(1) \)  \( \phi_{EW} \approx \phi_0; \)

• Below \( T_{EW}, \phi \) starts to oscilate around \( \phi_0, \) with amplitude \( \phi_{DM} \equiv x_{DM} \phi_0 \) (\( x_{DM} \lesssim 1; \)

The field *smoothly* changes from *dark radiation* to a *cold dark matter (CDM)* behavior as the *potential* becomes *quadratic* about the minimum.
SFDM dynamics – Constraints

• Idea: $\phi$ is never in *thermal equilibrium* with the cosmic plasma;

• **Constraints** on $g$ and $\lambda_\phi$ to prevent the *condensate evaporation* $\Rightarrow$ WIMP-like candidate;

  \begin{align*}
  &\text{Condensate evaporation} \quad \text{Higgs annihilation} \text{ into higher momentum } \phi \text{ particles;} \\
  &\text{Perturbative production of } \phi \text{ particles by the oscillating background condensate.}
  \end{align*}
SFDM dynamics – Constraints – Higgs annihilation

• Higgs annihilation for \( T \gtrsim T_{EW} \):

\[ \Gamma_{hh\rightarrow\phi\phi} = n_h \langle \sigma v \rangle \quad \text{and} \quad \sigma \approx \frac{g^4}{64 \pi} T^{-2} \left( 1 + \frac{m_h^2}{T^2} \right)^{-1} \]

• After the EWPT ⇒ **Higgs decay into SM** degrees of freedom ⇒ **\( \phi \)** production **stops** ⇒ require \( \Gamma_{hh\rightarrow\phi\phi} \lesssim H \) before the EWPT.

• Since \( \Gamma_{hh\rightarrow\phi\phi} \propto T \) and \( H_{rad} \propto T^2 \), stronger constraint at \( T_{EW} \):

\[ g < 8 \times 10^{-4} \left( \frac{g_*}{100} \right)^{1/8} \]
• Field can be decomposed into **background** + particle fluctuations $\delta \phi$;

• Production rate: [Ichikawa et al., 2008]

\[
\Gamma_{\phi \rightarrow \delta \phi \delta \phi} \approx 4 \times 10^{-2} \left( \frac{\lambda_{\phi}^3}{2} \phi \right)
\]

Valid for $T \gtrsim T_{\text{EW}}$

\[
\lambda_{\phi} < 6 \times 10^{-10} \left( \frac{g_*}{100} \right)^{1/5} \left( \frac{r}{0.01} \right)^{-1/5} \xi^{1/10}
\]

• This **limits** the viable DM mass range to $m_{\phi} < 1 \text{ MeV}$. 
SFDM phenomenology - $\phi$ decay into photons

- $\phi$ and $h$ scalars - small mass mixing, mixing parameter $\epsilon = \frac{g^2 \phi_0 v}{m_h^2}$;

- SFDM can decay into the same decay channels as the Higgs;

\[
\Gamma_{\phi \rightarrow \gamma \gamma} = \epsilon^2 \frac{g_F \alpha^2 F^2 m_\phi^3}{128 \sqrt{2} \pi^3}
\]

\[
\Gamma_{H^* \rightarrow \gamma \gamma}
\]

\[
\tau_{\phi} \simeq 7 \times 10^{27} \left( \frac{m_\phi}{7 \text{ keV}} \right)^{-5} \left( \frac{x_{DM}}{0.5} \right)^2 \text{ sec}
\]

\[
\tau_{\phi} \gg \tau_{\text{Uni}}
\]

Can lead to an observable monochromatic line in the spectrum of galaxies and galaxy clusters.

4/09/2018
Cosmological implications of the spontaneous symmetry breaking

Global U(1) symmetry

• $\phi$ decays into massless Goldstone bosons $\Rightarrow \lambda_\phi < 2 \times 10^{-32} \left( \frac{x_{DM}}{0.5} \right)^{2/5}$;

• In this case, $m_\phi < 5\; eV$; cannot explain the 3.5 keV line.

U(1) gauge symmetry

• Goldstone boson absorbed in the longitudinal component of the massive gauge boson;

• If the gauge boson acquires large mass $\Rightarrow \phi$ decay is kinematically blocked, requiring $e' > \sqrt{2\lambda_\phi}$ - not a significant constraint since $\lambda_\phi$ is very small.
Cosmic strings

- U(1) symmetry breaking ⇒ generation of cosmic strings at the EWPT;

\[ \frac{\rho_s}{\rho_c} \approx 10^{-6} \left( \frac{\phi_0}{10^{16} \text{GeV}} \right)^2 \] but \( \phi_0 \ll 10^{16} \text{GeV} \) even for very suppressed \( \lambda_\phi \) ⇒ no additional constraints;

- It is possible to achieve the dynamics and predictions of our model with a real scalar field and \( \mathbb{Z}_2 \) symmetry;

- Domain walls production, but this network may decay if there is a bias in the initial configuration of the field towards one of the potential minima, which could likely result from field fluctuations during inflation. [Larsson, Sarkar and White, 1997];

- Inflation may produce such a bias through the quantum fluctuations of the scalar field that become frozen on super-horizon scales. Dark scalar never thermalizes with the cosmic plasma ⇒ bias could survive until the EWPT ⇒ lead to the destruction of any domain wall network generated during the phase transition [Larsson, Sarkar and White, 1997];
SFDM phenomenology – Laboratory signatures

- $g$ is very small ⇒ **hard** to probe in the **lab**;

- Higgs decays into invisibles - $\Gamma_{h\rightarrow\phi\phi}\sim10^{-27}$ - too small to probe in near future;

- SFDM coupling to photons - **Light shining through wall experiments** (but conversion probabilities are very small);

- May induce **small oscillations of fundamental constants**, $m_e$ and $\alpha$ ⇒ detection using interferometry.
Effects of field self-interactions

- Interactions with the Higgs field $\Rightarrow$ quartic coupling for the DM:

$$\lambda \sim g^4$$

- After inflation, $\phi_i \sim \alpha H_{inf}$

Contribution to the DM field mass:

$$\Delta m^2_\phi \sim \lambda \phi_i^2 \sim g^4 H_{inf}^2$$

- Since

$$\frac{\Delta m^2_\phi}{m^2_\phi} \sim \frac{H_{inf}^2}{M^2_{Pl}} \ll 1$$

May neglect the effect of these self-interactions on the dynamics of the DM field.