

Scalar field dark matter with spontaneous symmetry breaking and the 3.5 keV line

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

- **Oscillating scalar field dark matter (SFDM)**, Φ , 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, λ_ϕ - SFDM self-coupling, ξ - 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

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

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

- $H_{inf} \simeq 2.5 \times 10^{13} \left(\frac{r}{0.01}\right)^{\frac{1}{2}} \text{ GeV}, r < 0.11$. [Planck Collaboration 2015].

$$r \equiv \frac{\Delta_t^2}{\Delta_{\mathcal{R}}^2}$$

- $m_\phi \simeq \sqrt{12 \xi} H_{inf} \gtrsim H_{inf}$ for $\xi \gtrsim 0.1 \Rightarrow$ **No observable isocurvature modes** in the CMB spectrum \Rightarrow **Compatible** with observations.

Inflation and initial conditions

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


$$|\delta\phi_k|^2 \simeq \left(\frac{H_{inf}}{2\pi}\right)^2 \frac{H_{inf}}{m_\phi} \frac{2\pi^2}{(aH_{inf})^3} \xrightarrow{\text{Integrating over all modes}} \langle\phi^2\rangle \simeq \alpha^2 H_{inf}^2$$

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

$$\phi_{inf} = \sqrt{\langle\phi^2\rangle} \simeq \alpha H_{inf} \qquad \alpha \simeq 0.05 \xi^{-1/4}$$

SFDM dynamics – Before the EWPT

- After inflation and the reheating \Rightarrow Radiation dominated epoch $\Rightarrow \mathbf{R = 0}$

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


- The field starts to oscillate at $T_{rad} = \left(\frac{270}{\pi^2 g_*} \right)^{1/4} (\phi_{inf} M_{Pl})^{1/2} \lambda_\phi^{1/4}$, with $\phi_{rad}(T) = \frac{\phi_{inf}}{T_{rad}} T$;
- Since $T \sim a^{-1}$, $\rho_\phi \sim a^{-4} \Rightarrow$ Field behaves like **dark radiation**.

SFDM dynamics – After the EWPT

- At the EWPT - still radiation era $\Rightarrow \mathbf{R} = \mathbf{0}$

$$-\mathcal{L}_{int} = -\frac{g^2}{4}\phi^2 h^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_h}{4}(h^2 - \tilde{v}^2)^2$$

Higgs vev

$$h_0 = \left(1 - \frac{g^4}{4\lambda_\phi\lambda_h}\right)^{-1/2} \tilde{v} \equiv v$$

ϕ vev

$$\phi_0 = \frac{gv}{\sqrt{2\lambda_\phi}}$$

$$v = 246 \text{ GeV}$$

- $T_{EW} \sim m_W$ - **Leading thermal contributions** to the Higgs potential are **Boltzmann-suppressed**
 $\Rightarrow \phi$ starts to oscillate about ϕ_0 .

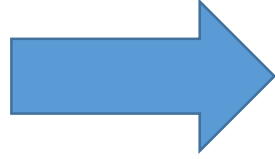
SFDM dynamics – After the EWPT

- ϕ starts to oscillate around ϕ_0 , with **initial amplitude** $\phi_{DM} \equiv x_{DM}\phi_0$ ($x_{DM} \lesssim 1$);
- Below T_{EW} , ϕ^2 dominates over ϕ^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: $\phi(T) = \phi_{DM} \left(\frac{T}{T_{EW}} \right)^{3/2}$



$$\frac{n_\phi}{s} = \frac{\rho_\phi/m_\phi}{\frac{2\pi^2}{45}g_*sT^3} = \text{const}$$

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

$$m_\phi = (6\Omega_{\phi,0})^{1/2} \left(\frac{g_*s}{g_{*s0}} \right)^{1/2} \left(\frac{T_{EW}}{T_0} \right)^{3/2} \frac{H_0 M_{Pl}}{\phi_{DM}}$$

- Also $m_\phi = gv$

$$g \simeq 2 \times 10^{-3} \left(\frac{x_{DM}}{0.5} \right)^{-1/2} \lambda_\phi^{1/4}$$

SFDM dynamics – Constraints

- Idea: ϕ is **never** in **thermal equilibrium** with the cosmic plasma;
- Need to **impose constraints** on g and λ_ϕ to prevent the **condensate evaporation** \Rightarrow WIMP-like candidate (WIMP- Weakly Interacting Massive Particle);

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

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



This **limits** the viable
DM mass range to
 $m_\phi < 1$ MeV.

SFDM phenomenology - ϕ decay into photons

- SFDM can decay into the same decay channels as the Higgs;
- $m_\phi < 1 \text{ MeV} \Rightarrow$ decay into photon pairs;

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

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



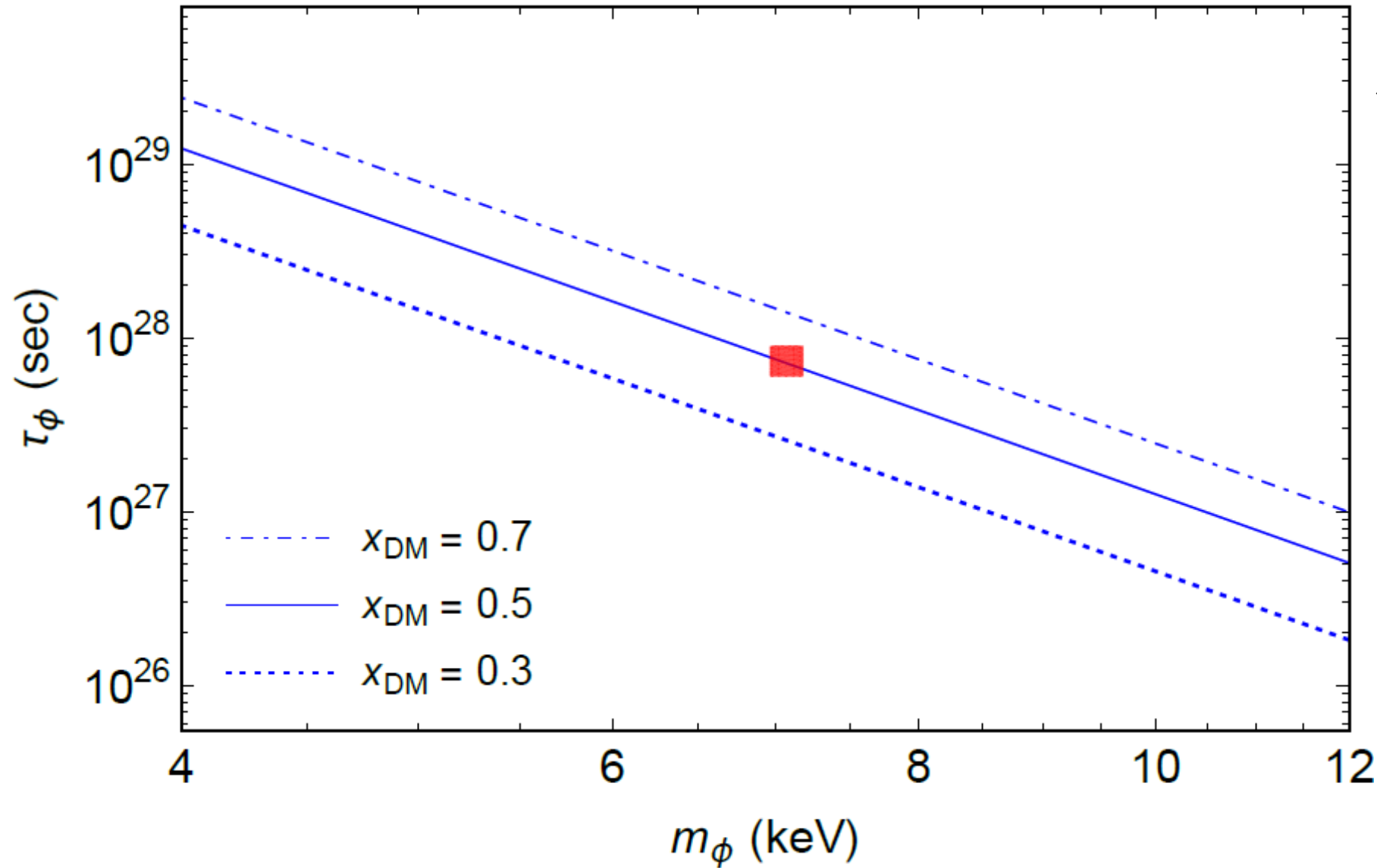
Can lead to an observable monochromatic line in the spectrum of galaxies and galaxy clusters.

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;

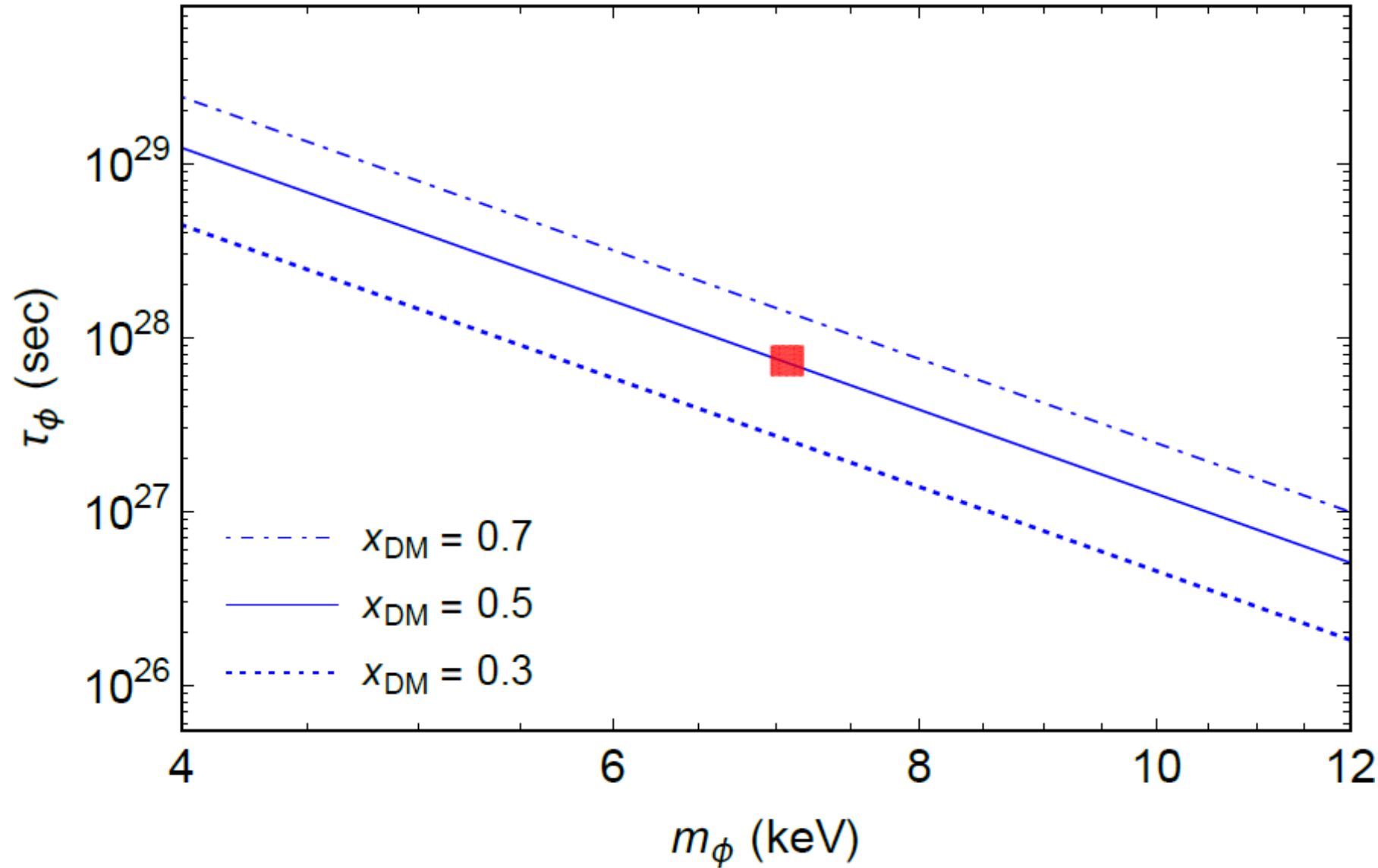
Decay of a DM particle with $m \simeq 7 \text{ keV}$ and $\tau \sim (6 - 9) \times 10^{27} \text{ sec}$ can explain the line observed in the Galactic Center, Andromeda and Perseus.

SFDM phenomenology – Model predictions



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

SFDM phenomenology – Model predictions



$$m_\phi = 7\text{keV}$$



$$g \simeq 3 \times 10^{-8}$$
$$\lambda_\phi \simeq 4 \times 10^{-20}$$

Satisfy the constraints
on g and λ_ϕ .

SFDM phenomenology – Model predictions

ξ

Suppresses the potential
CDM isocurvature
perturbations

r

Sets the amplitude
field at the onset of
radiation era

g

λ_ϕ

SFDM phenomenology – Model predictions

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Sets the amplitude
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λ_ϕ

- **After** the **EWPT**, the field oscillates about ϕ_0 - **only** depends on g and λ_ϕ .

SFDM phenomenology – Model predictions

~~ξ~~

Suppresses the potential
CDM isocurvature
perturbations

~~r~~

Sets the amplitude
field at the onset of
radiation era

g

λ_ϕ

- **After** the **EWPT**, the field oscillates about ϕ_0 - **only** depends on g and λ_ϕ .
- Present DM abundance, field mass and its decay – only dependent on g and λ_ϕ .

SFDM phenomenology – Model predictions



Suppresses the potential
CDM isocurvature
perturbations



Sets the amplitude
field at the onset of
radiation era

g

λ_ϕ

- **After** the **EWPT**, the field oscillates about ϕ_0 - **only** depends on g and λ_ϕ .
- Present DM abundance, field mass and its decay – only dependent on g and λ_ϕ .

SFDM accounts for all DM \Rightarrow Relation between g and λ_ϕ
 $\Rightarrow m_\phi$ and τ_ϕ 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

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**:

$$- \mathcal{L}_{int} = g^2 |\Phi|^2 |\mathcal{H}|^2$$

- Literature: **“Higgs-portal” DM models**: abundance of DM is set by the decoupling and freeze-out from **thermal equilibrium** $\Rightarrow m \sim GeV - TeV$ (Weakly Interacting Massive Particles - WIMPs) [Silveira, Zee 1985; Bento, Bertolami, Rosenfeld 2001; Burgess, Pospelov, ter Veldhuis 2001];
- Our candidate: **extremely small self-interactions** \Rightarrow 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 \Rightarrow Radiation dominated epoch $\Rightarrow \mathbf{R} = \mathbf{0}$



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

- EOM: $\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + V'(\phi) = 0$; when $m_\phi = \sqrt{3 \lambda_\phi} \phi > H$, field starts to **oscillate**;

friction term

- The field starts to oscillate at $T_{rad} = \left(\frac{270}{\pi^2 g_*}\right)^{1/4} (\phi_{inf} M_{Pl})^{1/2} \lambda_\phi^{1/4}$, with $\phi_{rad}(T) = \frac{\phi_{inf}}{T_{rad}} T$;
- Since $T \sim a^{-1}$, $\rho_\phi \sim a^{-4} \Rightarrow$ Field behaves like **dark radiation**.

SFDM dynamics – After the EWPT

- Recall: $\phi_{EW} = \frac{\phi_{inf}}{T_{rad}} T_{EW}$  $\phi_{EW} \simeq 10^{-4} g_*^{1/4} \xi^{-1/8} \left(\frac{r}{0.01}\right)^{1/4} \frac{\lambda_\phi^{1/4}}{g} \phi_0$;
- **Note:** $g \gtrsim 10^{-4} \lambda_\phi^{1/4}$, $\xi \sim \mathcal{O}(1)$  $\phi_{EW} \lesssim \phi_0$;
- Below T_{EW} , ϕ starts to oscillate around ϕ_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: ϕ is **never** in **thermal equilibrium** with the cosmic plasma;



- **Constraints** on g and λ_ϕ to prevent the **condensate evaporation** \Rightarrow WIMP-like candidate;

**Condensate
evaporation**

Higgs annihilation into higher momentum ϕ particles;

Perturbative **production** of ϕ particles by the **oscillating background condensate**.

SFDM dynamics – Constraints – Higgs annihilation

- Higgs annihilation for $T \gtrsim T_{EW}$:

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

- After the EWPT \Rightarrow **Higgs decay into SM** degrees of freedom \Rightarrow ϕ production **stops** \Rightarrow 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} :

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

SFDM dynamics – Constraints – Perturbative production

- Field can be decomposed into **background** + particle fluctuations $\delta\phi$;
- Production rate: [Ichikawa et al., 2008]

$$\Gamma_{\phi \rightarrow \delta\phi\delta\phi} \simeq 4 \times 10^{-2} \lambda_{\phi}^{3/2} \phi \quad \text{Valid for } T \gtrsim T_{EW}$$

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

- This **limits** the viable DM mass range to $m_{\phi} < 1 \text{ MeV}$.

SFDM phenomenology - ϕ decay into photons

- ϕ 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;

$$\Gamma_{\phi \rightarrow \gamma\gamma} = \epsilon^2 \underbrace{\frac{G_F \alpha^2 F^2 m_\phi^3}{128\sqrt{2} \pi^3}}_{\Gamma_{H^* \rightarrow \gamma\gamma}}$$



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

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

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

Cosmological implications of the spontaneous symmetry breaking

Global U(1) symmetry

- ϕ decays into massless Goldstone bosons $\Rightarrow \lambda_\phi < 2 \times 10^{-32} \left(\frac{x_{DM}}{0.5}\right)^{2/5}$;
- In this case, $m_\phi < 5 \text{ eV}$; 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 λ_ϕ is very small.

Cosmic strings

- U(1) symmetry breaking \Rightarrow generation of **cosmic strings** at the EWPT;
- $\frac{\rho_s}{\rho_c} \simeq 10^{-6} \left(\frac{\phi_0}{10^{16} \text{ GeV}} \right)^2$ but $\phi_0 \ll 10^{16} \text{ GeV}$ even for **very suppressed** $\lambda_\phi \Rightarrow$ 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 \Rightarrow **bias could survive until the EWPT** \Rightarrow lead to the **destruction** of any **domain wall network** generated during the phase transition [Larsson, Sarkar and White, 1997];

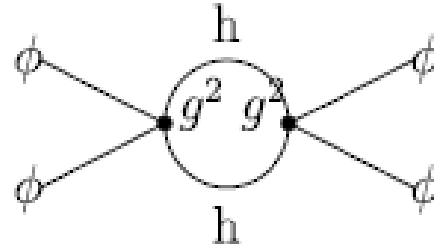
SFDM phenomenology – Laboratory signatures

- g is very small \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.

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:

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

- Since

$$\frac{\Delta m_\phi^2}{m_\phi^2} \sim \frac{H_{inf}^2}{M_{Pl}^2} \ll 1$$



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