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

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in collaboration with

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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**):

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

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

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

- **Scale-invariance of the full theory** that is broken somehow ⇒ negative squared mass to the Higgs ⇒ SFDM mass;

- **U(1) gauge** symmetry, negative coupling ⇒ Spontaneously **broken**; **DM** field may **decay** ⇒ 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, $\mathrm{R} \simeq 12\, H_{inf}^2$.
- $H_{inf} \simeq 2.5\times 10^{13}\left(\frac{r}{0.01}\right)^{\frac{1}{2}}\ GeV,\ r < 0.11.$ [Planck Collaboration 2015]. $\boxed{r \equiv \frac{\Delta_t^2}{\Delta_{\mathcal{R}}^2}}$
- $m_\phi \simeq \sqrt{12\,\xi}\ H_{inf} \gtrsim H_{inf}$ 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 $\left(\frac{m_\phi}{H_{inf}} > \frac{3}{2}\right)$:

Integrating over all modes

$$|\delta\phi_k|^2 \simeq \left(\frac{H_{inf}}{2\pi}\right)^2 \frac{H_{inf}}{m_\phi} \frac{2\pi^2}{\left(aH_{inf}\right)^3} \longrightarrow \langle\phi^2\rangle \simeq \alpha^2 H_{inf}^2$$

- $\langle\boldsymbol{\phi}^2\rangle$ **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 ⇒ Radiation dominated epoch ⇒ $\boldsymbol{R = 0}$

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

- 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

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

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

Higgs vev

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

$\boldsymbol{\phi}$ **vev**

$$\boxed{\phi_0 = \frac{g\text{v}}{\sqrt{2\lambda_\phi}}}$$

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

- $T_{EW} \sim m_W$ - **Leading thermal contributions** to the Higgs potential are **Boltzmann-suppressed**

$\Rightarrow \boldsymbol{\phi}$ starts to oscillate about ϕ_0.

SFDM dynamics – After the EWPT

- ϕ starts to oscilate around ϕ_0, with **initial amplitude $\boldsymbol{\phi_{DM} \equiv x_{DM}\phi_0}$** ($x_{DM} \lesssim 1$);

- Below $\boldsymbol{T_{EW}}$, $\boldsymbol{\phi^2}$ 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: $\phi(T) = \phi_{DM}\left(\frac{T}{T_{EW}}\right)^{3/2}$ $\Rightarrow$ $\boxed{\frac{n_\phi}{s} = \frac{\rho_\phi/m_\phi}{\frac{2\pi^2}{45}g_{*S}T^3} = \text{const}}$

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

$$m_\phi = (6\Omega_{\phi,0})^{1/2}\left(\frac{g_{*S}}{g_{*S0}}\right)^{1/2}\left(\frac{T_{EW}}{T_0}\right)^{3/2}\frac{H_0 M_{Pl}}{\phi_{DM}}$$

- Also $m_\phi = g\mathrm{v}$

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

SFDM dynamics – Constraints

- Idea: $\boldsymbol{\phi}$ is **never** in **thermal equilibrium** with the cosmic plasma;

- Need to **impose constraints** on $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$ to prevent the **condensate evaporation** $\Rightarrow$ WIMP-like candidate (WIMP- Weakly Interacting Massive Particle);

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

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

$\Downarrow$

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

SFDM phenomenology - ϕ decay into photons

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

- $\boldsymbol{m_\phi < 1\ \mathrm{MeV}}$ $\Rightarrow$ decay into photon pairs;

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

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

$\Downarrow$

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

The 3.5 keV line

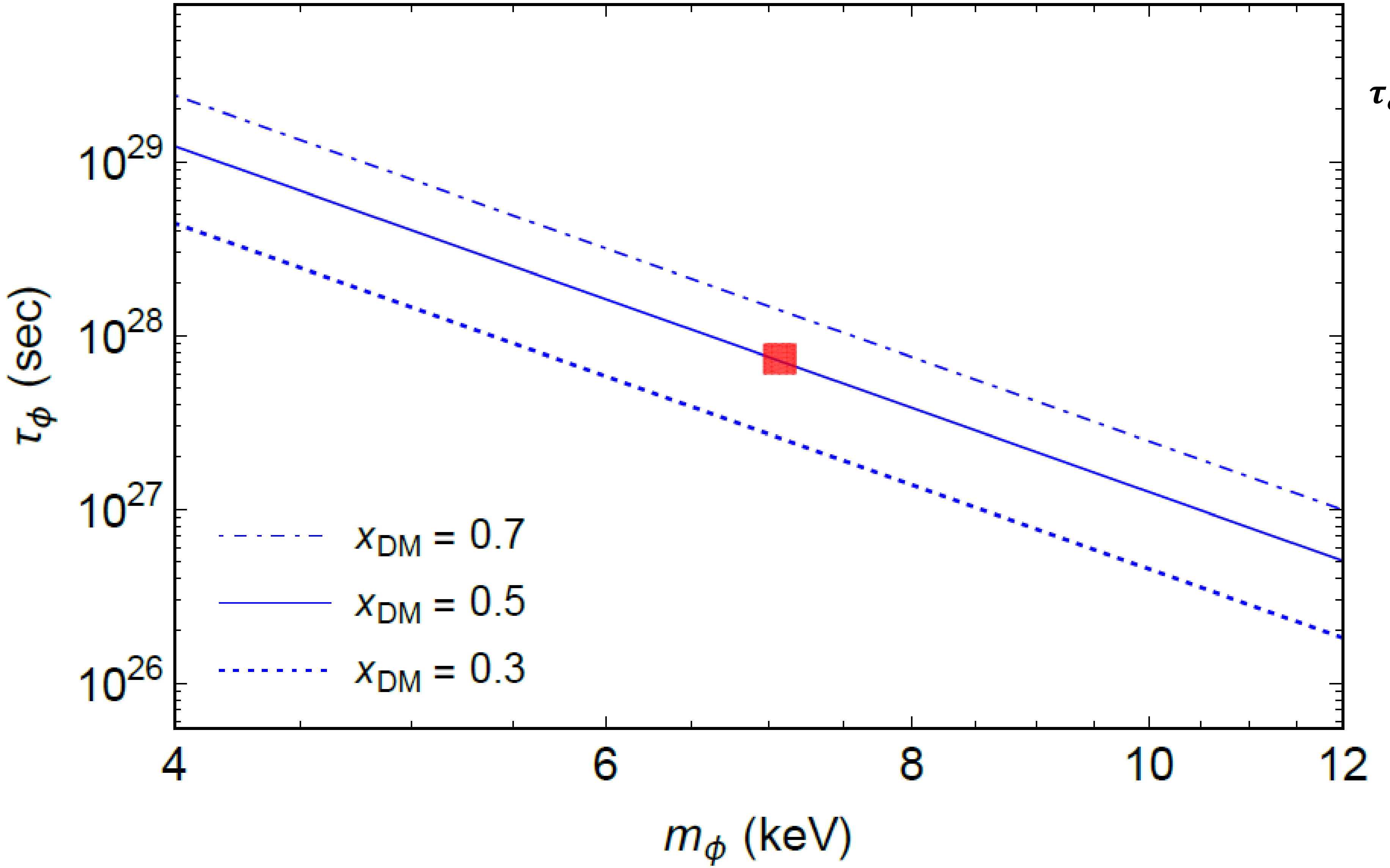
- XMM-Newton X-ray observatory discovered a **3.5 keV line** in the Galactic Center, Andromeda and Perseus cluster [Bulbul et al., 2014; Boyarski et al., 2014; Cappelluti et al., 2017] ;

- 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;

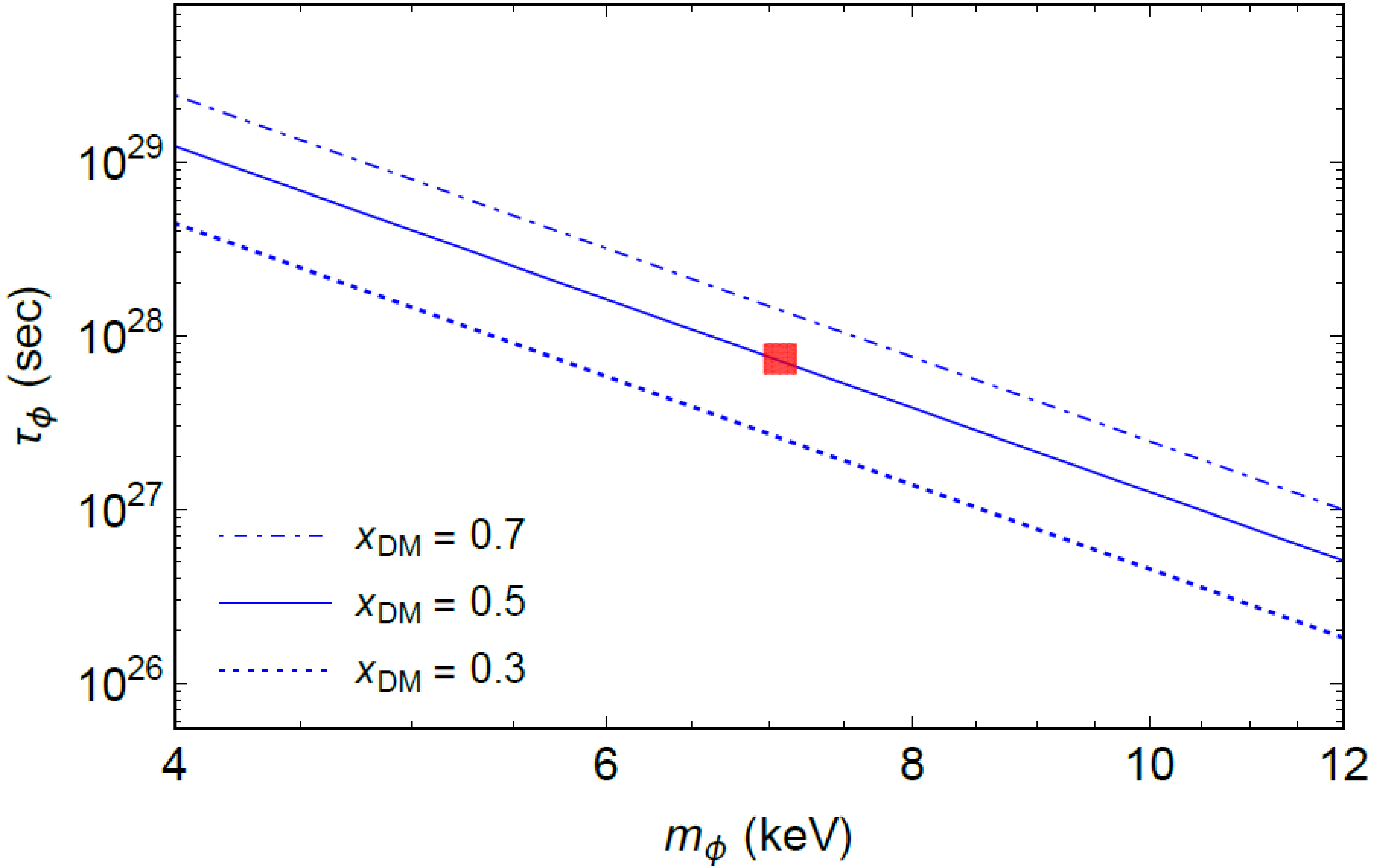
Decay of a DM particle with $\boldsymbol{m \simeq 7\,\mathrm{keV}}$ and $\boldsymbol{\tau \sim (6-9) \times 10^{27}}$ **sec** can explain the line observed in the Galactic Center, Andromeda and Perseus.

SFDM phenomenology – Model predictions



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

SFDM phenomenology – Model predictions



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

$$\Downarrow$$

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

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

ξ	r	g	λ_ϕ
Suppresses the potential CDM isocurvature perturbations	Sets the amplitude field at the onset of radiation era		

- **After** the **EWPT**, the field oscillates about ϕ_0 - **only** depends on $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$.

SFDM phenomenology – Model predictions

$\cancel{\xi}$

Suppresses the potential CDM isocurvature perturbations

$\cancel{r}$

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 $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$.
- Present DM abundance, field mass and its decay – only dependent on $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$.

SFDM phenomenology – Model predictions

$\cancel{\xi}$	$\cancel{r}$	g	λ_ϕ
Suppresses the potential CDM isocurvature perturbations	Sets the amplitude field at the onset of radiation era		

- **After** the **EWPT**, the field oscillates about ϕ_0 - **only** depends on $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$.

- Present DM abundance, field mass and its decay – only dependent on $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$.

$\boxed{\text{SFDM accounts for all DM} \Rightarrow \text{Relation between } \boldsymbol{g} \text{ and } \boldsymbol{\lambda_\phi}}$

SFDM accounts for all DM $\Rightarrow$ Relation between $\boldsymbol{g}$ and $\boldsymbol{\lambda_\phi}$
$\Rightarrow$ $\boldsymbol{m_\phi}$ **and** $\boldsymbol{\tau_\phi}$ 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

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 [Rodrigez-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 ⇒ Radiation dominated epoch ⇒ $\boldsymbol{R = 0}$

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

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

- 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: $\phi_{EW} = \frac{\phi_{inf}}{T_{rad}} T_{EW}$ $\Longrightarrow$ $\phi_{EW} \simeq 10^{-4} g_*^{1/4} \xi^{-1/8} \left(\frac{r}{0.01}\right)^{1/4} \frac{\lambda_\phi^{1/4}}{g}\, \phi_0;$

- **Note:** $g \gtrsim 10^{-4}\, \lambda_\phi^{1/4}, \xi \sim \mathcal{O}(1)$ $\Longrightarrow$ $\phi_{EW} \lesssim \phi_0;$

- Below $\boldsymbol{T_{EW}}$, ϕ starts to oscilate around ϕ_0, with **amplitude** $\boldsymbol{\phi_{DM} \equiv x_{DM}\phi_0}$ ($x_{DM} \lesssim 1$);

The field **smootlhy** changes from **dark radiation** to a **cold dark matter (CDM)** behavior as the **potential** becomes **quadratic** about the minimum.

SFDM dynamics – Constraints

- Idea: $\boldsymbol{\phi}$ is **never** in **thermal equilibrium** with the cosmic plasma;

- **Constraints** on $\boldsymbol{g}$ and $\boldsymbol{\lambda_{\phi}}$ 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 $T \gtrsim T_{EW}$:

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

- After the EWPT ⇒ **Higgs decay into SM** degrees of freedom ⇒ $\boldsymbol{\phi}$ production **stops** ⇒ require $\boldsymbol{\Gamma_{hh\to\phi\phi} \lesssim H}$ before the EWPT.

- Since $\Gamma_{hh\to\phi\phi} \propto T$ and $H_{rad} \propto T^2$, stronger constraint at T_{EW}:

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

SFDM dynamics – Constraints – Perturbative production

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

$$\Gamma_{\phi\to\delta\phi\delta\phi} \simeq 4\times 10^{-2}\,\lambda_\phi^{3/2}\phi$$

Valid for $T \gtrsim T_{EW}$

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

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

SFDM phenomenology - ϕ decay into photons

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

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

$$\Gamma_{\phi\to\gamma\gamma} = \epsilon^2 \underbrace{\frac{G_F\alpha^2F^2\,m_\phi^3}{128\sqrt{2}\,\pi^3}}_{\Gamma_{H^*\to\gamma\gamma}} \quad \Rightarrow \quad \boxed{\tau_\phi \simeq 7\times 10^{27}\left(\frac{m_\phi}{7\,\mathrm{keV}}\right)^{-5}\left(\frac{x_{DM}}{0.5}\right)^2 \ \mathrm{sec}} \qquad \tau_\phi \gg \tau_{Uni}$$

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, $m_\phi < 5\ eV$; 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 $\Rightarrow$ ϕ 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;
- $\frac{\rho_s}{\rho_c} \simeq 10^{-6}\left(\frac{\phi_0}{10^{16}\,GeV}\right)^2$ but $\boldsymbol{\phi_0} \ll \mathbf{10^{16}}$ **GeV** even for **very suppressed** $\boldsymbol{\lambda_\phi} \Rightarrow$ 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 ⇒ **hard** to probe in the **lab**;

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

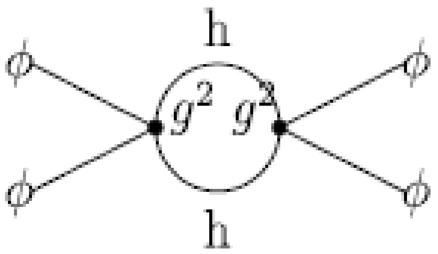
- SFDM coupling to photons - **Light shining through wall experiments** (but conversion probabilities are very small);

- May induce **small oscillations of fundamental constants**, m_e and α ⇒ detection using interferometry.

Effects of field self-interactions

- Interactions with the Higgs field ⇒ quartic coupling for the DM:

$$\boxed{\lambda \sim g^4}$$



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

Contribution to the DM field mass:

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

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

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