# Scalar field dark matter and the Higgs field

Catarina M. Cosme

in collaboration with

João Rosa and Orfeu Bertolami

*Phys. Lett.*, B759:1-8, 2016

COSMO-17, Paris Diderot University, 29 August 2017

U.PORTO
FACULDADE DE CIÊNCIAS
UNIVERSIDADE DO PORTO

MAP JOINT DOCTORAL PROGRAMMES

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

# Outline

- Introduction and Motivation;
- Oscillating scalar field as dark matter candidate;
- Inflation and initial conditions;
- Possible scenarios
  - Non-renormalizable interactions model;
  - Warped extra-dimension model;
- Conclusions and future work.

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];
  - Evidence of DM come from different sources;

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];
  - Evidence of DM come from different sources;
  - Several candidates;

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];
  - Evidence of DM come from different sources;
  - Several candidates;

**What is dark matter made of?**

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];
  - Evidence of DM come from different sources;
  - Several candidates;

**What is dark matter made of?**

- We propose: oscillating scalar field as DM candidate, coupled to the Higgs boson;

# Introduction and motivation

- **Dark matter (DM)**
  - **26.8 %** of the mass-energy content of the Universe [Planck Collaboration 2015];
  - Evidence of DM come from different sources;
  - Several candidates;

**What is dark matter made of?**

- We propose: oscillating scalar field as DM candidate, coupled to the Higgs boson;
- Previous works: **"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; Tenkanen 2015].

# Oscillating scalar field as DM candidate

## Our proposal:

- Oscillating scalar field, $\phi$, as DM candidate;
- $\phi$ acquires mass through the Higgs mechanism;
- Feeble interactions with the Higgs boson $\Rightarrow$ $m_\phi \ll eV$ ; extremely small self-interactions $\Rightarrow$ oscillating scalar condensate that is never in thermal equilibrium.

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \, \phi = 0$

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2 \, \phi = 0$$

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\,\phi = 0$$

friction term

**Before** the electroweak phase transition (**EWPT**) ($T \sim 100$ GeV): $\boldsymbol{m_\phi < H}$

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\,\phi = 0$$

friction term

**Before** the electroweak phase transition (**EWPT**) ($T \sim 100$ GeV): $\boldsymbol{m_\phi < H}$ ⇒ Overdamped regime.

No oscillations.

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\, \phi = 0$$

**Before** the electroweak phase transition (**EWPT**) ($T \sim 100$ GeV): $\boldsymbol{m_\phi < H}$ $\Rightarrow$ Overdamped regime.

No oscillations.

**After** the **EWPT**: $\boldsymbol{m_\phi > H}$

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\, \phi = 0$$

**Before** the electroweak phase transition (**EWPT**) ($T \sim 100$ GeV): $\boldsymbol{m_\phi < H}$ ⇒ Overdamped regime.

No oscillations.

**After** the **EWPT**: $\boldsymbol{m_\phi > H}$ ⇒ Underdamped regime. The field oscillates.

# Oscillating scalar field as DM candidate

## When does it start to oscillate?

KG: $$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\,\phi = 0$$

**Before** the electroweak phase transition (**EWPT**) ($T \sim 100$ GeV): $\boldsymbol{m_\phi < H}$ $\Rightarrow$ Overdamped regime.

No oscillations.

**After** the **EWPT**: $\boldsymbol{m_\phi > H}$ $\Rightarrow$ Underdamped regime. The field oscillates.

$$H_{rad} = \frac{\pi}{\sqrt{90}}\sqrt{g_*}\frac{T^2}{M_{Pl}}$$

$$\rho_{\phi,0} = \frac{1}{2}\frac{m_\phi^2}{a_0^3}\phi_i^2$$

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

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*S,0}}{g_{*S}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

$T_{osc}$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6 H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$

$T_{EW}$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6 H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$

$T_{EW}$

$$m_\phi(\phi_i) = 2 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-1} eV$$

# Oscillating scalar field as DM candidate

$H_{EW} \sim 10^{-5}\ eV$

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2\, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$

$m_\phi < H$ at $T_{EW}$

$T_{EW}$

$$m_\phi(\phi_i) = 2 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-1} eV$$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2 \, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5} \; eV$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$

$m_\phi < H$ at $T_{EW}$

$T_{EW}$

$T = \left(\frac{90}{\pi^2}\right)^{1/4} g_*^{-1/4} \sqrt{M_{Pl} m_\phi}$

$$m_\phi(\phi_i) = 2 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{\phi_i}{10^{13}\; GeV}\right)^{-1} eV$$

# Oscillating scalar field as DM candidate

DM abundance: $\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi^2\, {\phi_i}^2}{6H_0^2 M_{Pl}^2} \frac{g_{*s,0}}{g_{*s}} \frac{T_0}{T_{osc}^3}$

$H_{EW} \sim 10^{-5}\ eV$

$T_{osc}$

$m_\phi > H$ at $T_{EW}$ → $T_{EW}$ →

$$m_\phi(\phi_i) = 2 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-1} eV$$

$m_\phi < H$ at $T_{EW}$ → $T = \left(\frac{90}{\pi^2}\right)^{1/4} g_*^{-1/4} \sqrt{M_{Pl} m_\phi}$ →

$$m_\phi(\phi_i) = 3 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{\phi_i}{10^{13}\ GeV}\right)^{-4} eV$$

# Inflation and initial conditions

- If the **Higgs field** is the **unique source of mass** during inflation $\Rightarrow m_{\phi} \sim \mathcal{O}(\text{EW scale}) \Rightarrow$ **Light field** $\Rightarrow$ de-Sitter fluctuations $\sim \frac{H_{inf}}{2\pi} \Rightarrow$ sizeable Cold Dark Matter (CDM) isocuvature modes in the CMB spectrum $\Rightarrow$ **ruled out** (do not respect the observational constraints on the CDM isocurvature perturbations).

# Inflation and initial conditions

- If the **Higgs field** is the **unique source of mass** during inflation $\Rightarrow m_{\phi} \sim \mathcal{O}(\text{EW scale}) \Rightarrow$ **Light field** $\Rightarrow$ de-Sitter fluctuations $\sim \frac{H_{inf}}{2\pi}$ $\Rightarrow$ sizeable Cold Dark Matter (CDM) isocuvature modes in the CMB spectrum $\Rightarrow$ **ruled out** (do not respect the observational constraints on the CDM isocurvature perturbations).

- **Gravitational interactions** during inflation $\Rightarrow \mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2} \Rightarrow m_{\phi} \sim H_{inf} \Rightarrow$ **Massive field**;

# Inflation and initial conditions

- If the **Higgs field** is the **unique source of mass** during inflation $\Rightarrow m_\phi \sim \mathcal{O}(\text{EW scale}) \Rightarrow$ **Light field** $\Rightarrow$ de-Sitter fluctuations $\sim \frac{H_{inf}}{2\pi}$ $\Rightarrow$ sizeable Cold Dark Matter (CDM) isocuvature modes in the CMB spectrum $\Rightarrow$ **ruled out** (do not respect the observational constraints on the CDM isocurvature perturbations).

- **Gravitational interactions** during inflation $\Rightarrow \mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2} \Rightarrow m_\phi \sim H_{inf} \Rightarrow$ **Massive field**;

- Constraints on CDM isocurvature perturbations lead to: $\phi_i \simeq \alpha\, H_{inf}, \quad \alpha \simeq 0.1 - 0.25;$

# Inflation and initial conditions

- If the **Higgs field** is the **unique source of mass** during inflation $\Rightarrow m_\phi \sim \mathcal{O}$(EW scale) $\Rightarrow$ **Light field** $\Rightarrow$ de-Sitter fluctuations $\sim \frac{H_{inf}}{2\pi}$ $\Rightarrow$ sizeable Cold Dark Matter (CDM) isocuvature modes in the CMB spectrum $\Rightarrow$ **ruled out** (do not respect the observational constraints on the CDM isocurvature perturbations).

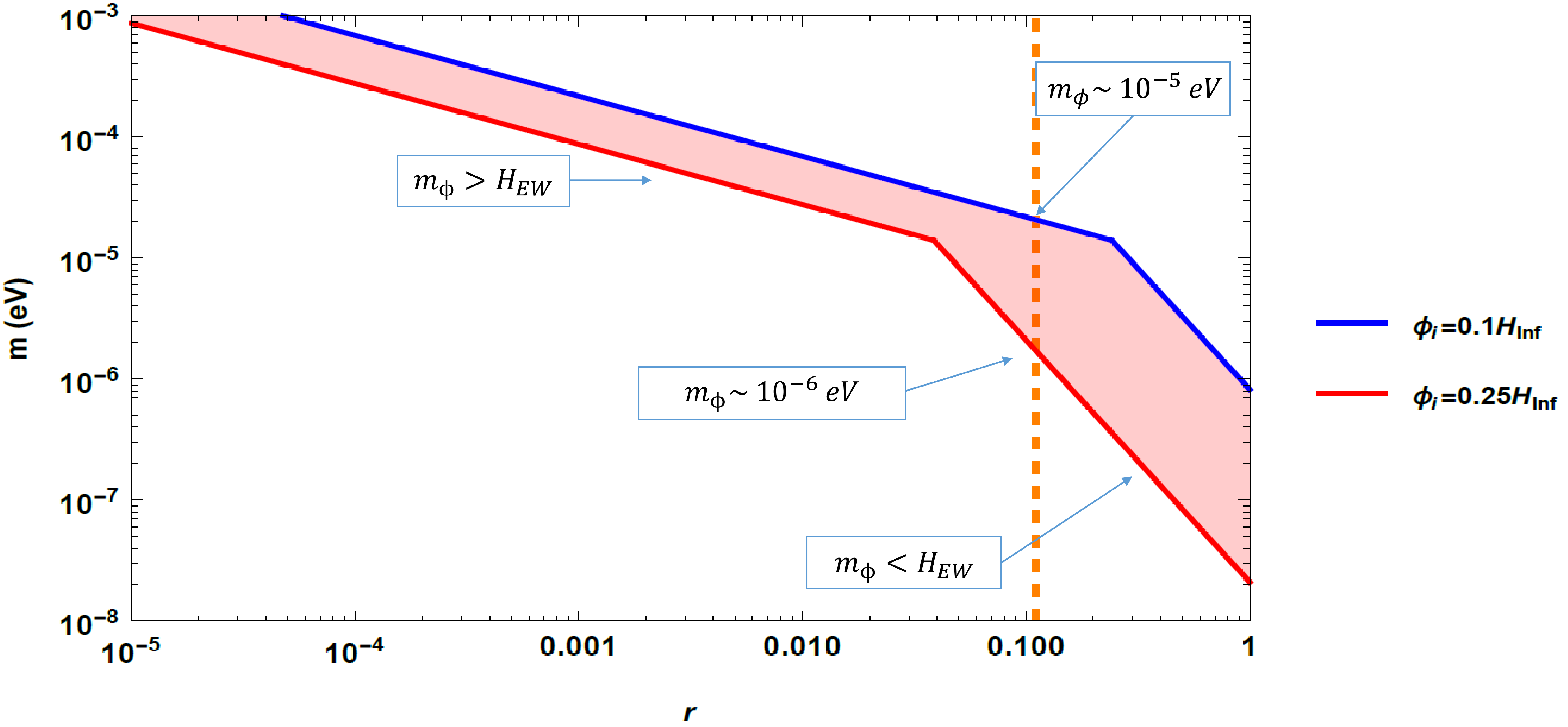
- **Gravitational interactions** during inflation $\Rightarrow$ $\mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2}$ $\Rightarrow$ $m_\phi \sim H_{inf}$ $\Rightarrow$ **Massive field**;

- Constraints on CDM isocurvature perturbations lead to: $\phi_i \simeq \alpha\, H_{inf}, \quad \alpha \simeq 0.1 - 0.25;$

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

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

# Initial conditions – Results



# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

Heavy messengers,

Gravity

# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

Heavy messengers,

Gravity

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

$$\mathcal{L}_{int} = \frac{a_6^2}{2}|h|^4\frac{\phi^2}{M^2}$$

# Non-renormalizable interactions model

| **Hidden sector** |
| --- |
| DM field |

| **Visible sector** |
| --- |
| Higgs boson (and Standard Model fields) |

Heavy messengers,

Gravity

$$\mathcal{L}_{int} = \frac{a_6^2}{2}|h|^4\frac{\phi^2}{M^2} \Rightarrow$$

Electroweak symmetry breaking

# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

Heavy messengers,

Gravity

$$\mathcal{L}_{int} = \frac{a_6^2}{2}|h|^4\frac{\phi^2}{M^2} \Rightarrow m_\phi = a_6\frac{v^2}{M} \sim 2.5\times 10^{-5}\, a_6\left(\frac{M}{M_{Pl}}\right)^{-1}\ \text{eV};$$

Electroweak symmetry breaking

# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

Heavy messengers,

Gravity

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

$$\mathcal{L}_{int} = \frac{a_6^2}{2}|h|^4 \frac{\phi^2}{M^2} \Rightarrow m_\phi = a_6 \frac{v^2}{M} \sim 2.5 \times 10^{-5}\ a_6 \left(\frac{M}{M_{Pl}}\right)^{-1} \text{eV};$$

Electroweak symmetry breaking

- If $M = M_{Pl} \Rightarrow m_\phi \sim 10^{-5}$ eV

# Non-renormalizable interactions model

| Hidden sector |
| --- |
| DM field |

| Visible sector |
| --- |
| Higgs boson (and Standard Model fields) |

Heavy messengers,

Gravity

$$\mathcal{L}_{int} = \frac{a_6^2}{2} |h|^4 \frac{\phi^2}{M^2} \Rightarrow m_\phi = a_6 \frac{v^2}{M} \sim 2.5 \times 10^{-5} \; a_6 \left(\frac{M}{M_{Pl}}\right)^{-1} \; \mathrm{eV};$$

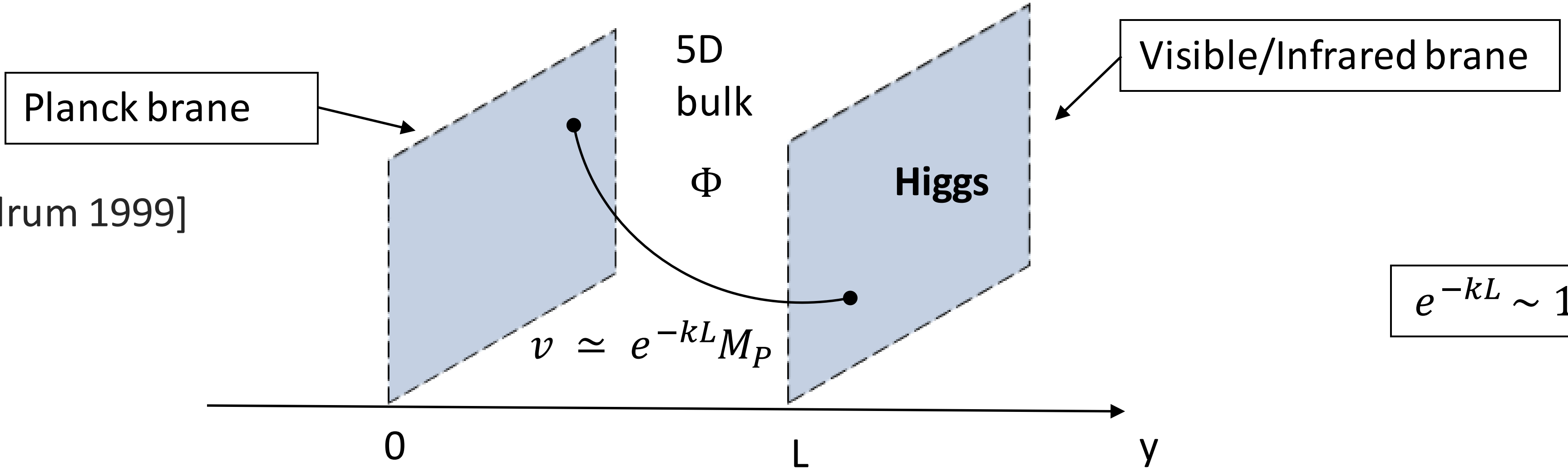
Electroweak symmetry breaking

- If $M = M_{Pl} \Rightarrow m_\phi \sim 10^{-5}$ eV → Interesting hierarchy: $\frac{m_\phi}{v} \sim \frac{v}{M_{Pl}}$

# Warped extra-dimension model

**Randall-Sundrum inspired model:**

[L. Randall, R. Sundrum 1999]




$e^{-kL} \sim 10^{-16}$

Metric: $ds^2 = e^{-2k|y|} g_{\mu\nu} dx^\mu dx^\nu + dy^2$

$$S = \int d^4x \int dy\, \sqrt{-G} \left[ \frac{1}{2} G^{MN} \partial_M \Phi \partial_N \Phi - \frac{1}{2} M_\Phi^2 \Phi^2 + \delta(y - L) \left( G^{MN} \partial_M h^\dagger \partial_N h - V(h) + \frac{1}{2} g_5^2 \Phi^2 h^2 \right) \right]$$

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;
- The DM field corresponds to the **zero-mode** : $f_0(y) \simeq \sqrt{2kL}$ ;

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;

- The DM field corresponds to the **zero-mode** : $f_0(y) \simeq \sqrt{2kL}$ ;

- $\Phi_0(x^\mu, L) = \phi_0(x^\mu)\sqrt{k}$ ➡ $$\mathcal{L}_{int} = \frac{1}{2} g_5^2 k e^{-2kL} \phi_0^2 h^2$$ Rescale: $h \to e^{kL} h$

➡ $$g_4 \sim \sqrt{g_5^2 k e^{-kL}} \simeq \mathcal{O}(1) \times \frac{v}{M_{Pl}} \sim 10^{-16}$$

$g_5^2 \sim \frac{1}{k}; \; k \simeq M_{Pl}$

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;
- The DM field corresponds to the **zero-mode** : $f_0(y) \simeq \sqrt{2kL}$ ;
- $\Phi_0(x^\mu, L) = \phi_0(x^\mu)\sqrt{k}$ ⇒ $\mathcal{L}_{int} = \frac{1}{2} g_5^2 k e^{-2kL} \phi_0^2 h^2$ Rescale: $h \to e^{kL} h$

⇒ $g_4 \sim \sqrt{g_5^2 k e^{-kL}} \simeq \mathcal{O}(1) \times \frac{v}{M_{Pl}} \sim 10^{-16}$

$g_5^2 \sim \frac{1}{k}; \, k \simeq M_{Pl}$

$$m_\phi \sim \frac{v^2}{M_{Pl}} \sim 10^{-5}\ \text{eV}$$

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;
- The DM field corresponds to the **zero-mode** : $f_0(y) \simeq \sqrt{2kL}$ ;
- $\Phi_0(x^\mu, L) = \phi_0(x^\mu)\sqrt{k}$ ⇒ $\mathcal{L}_{int} = \frac{1}{2} g_5^2 k e^{-2kL} \phi_0^2 h^2$  Rescale: $h \to e^{kL} h$

⇒ $g_4 \sim \sqrt{g_5^2 k e^{-kL}} \simeq \mathcal{O}(1) \times \frac{v}{M_{Pl}} \sim 10^{-16}$

$g_5^2 \sim \frac{1}{k}; \, k \simeq M_{Pl}$

$$m_\phi \sim \frac{v^2}{M_{Pl}} \sim 10^{-5}\ \mathrm{eV}$$

Mass in the required range.
Interesting hierarchy again:

$$\frac{m_\phi}{v} \sim \frac{v}{M_{Pl}}$$

# Warped extra-dimension model

- Decompose $\Phi$ into Kaluza-Klein modes: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$ ;
- The DM field corresponds to the **zero-mode** : $f_0(y) \simeq \sqrt{2kL}$ ;
- $\Phi_0(x^\mu, L) = \phi_0(x^\mu)\sqrt{k}$ ⇒ $\mathcal{L}_{int} = \frac{1}{2} g_5^2 k e^{-2kL} \phi_0^2 h^2$     Rescale: $h \to e^{kL} h$

⇒ $g_4 \sim \sqrt{g_5^2 k e^{-kL}} \simeq \mathcal{O}(1) \times \frac{v}{M_{Pl}} \sim 10^{-16}$

$g_5^2 \sim \frac{1}{k}; \ k \simeq M_{Pl}$

$$m_\phi \sim \frac{v^2}{M_{Pl}} \sim 10^{-5}\ \text{eV}$$

Mass in the required range.
Interesting hierarchy again:

$$\frac{m_\phi}{v} \sim \frac{v}{M_{Pl}}$$

Planck-suppressed non-renormalizable operator ⇔ Renormalizable interaction in a higher-dimensional warped geometry.

# Conclusions & Future work

- DM candidate: oscillating scalar field ϕ, which acquires mass through the Higgs mechanism.
- Lower bound: $m_\phi \gtrsim 10^{-6} - 10^{-5}\, eV$ ;
- $m_\phi \sim \frac{v^2}{M_P} \sim 10^{-5}\, eV$ obtained through either non-renormalizable interactions between ϕ and the Higgs field or through a warped extra-dimension model.
- **Future work**:
  - Extend the model – study the effect of self-interactions;
  - Find out ways of testing our model (astrophysical signatures, ongoing experiments...);

**Thank you for your attention!**

# Backup slides

# Introducing the problem – Dark Matter

**26.8%** of the mass-energy content of the Universe [Planck Collaboration 2015].

**Dark Matter (DM)**

**Candidates:**

- Weakly Interacting Massive Particles (WIMPs);
- Axions;
- Supersymmetric particles;
- ...

**Evidence from:**

- Galaxy rotation curve;
- Gravitational lensing;
- Anisotropies of the CMB;
- Bullet Cluster;

# 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];

# Oscillating scalar field as DM candidate

**Does an oscillating scalar field behave like non-relativistic matter?**

Potential: $V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$

Generic cosmological epoch: $a(t) = \left(\frac{t}{t_i}\right)^p, p > 0.$ Hubble parameter: $H = \frac{p}{t}$

Klein-Gordon (KG) eq. :

$$\ddot{\phi} + 3\frac{p}{t}\dot{\phi} + m_\phi^2 \phi = 0 \xrightarrow{m_\phi t \gg 1} \phi(t) \simeq \frac{\phi_i}{a(t)^{\frac{3}{2}}} \cos(m_\phi t + \delta_\phi)$$

Energy density: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \sim a^{-3}$ → Non-relativistic matter.

# Inflation and initial conditions

- If the **Higgs field** is the **unique source of mass** during inflation $\Rightarrow m_\phi \sim \mathcal{O}$(EW scale) $\Rightarrow$ **Light field** $\Rightarrow$ de-Sitter fluctuations $\sim \frac{H_{inf}}{2\pi}$ $\Rightarrow$ sizeable Cold Dark Matter (CDM) isocuvature modes in the CMB spectrum $\Rightarrow$ **ruled out** (do not respect the observational constraints on the CDM isocurvature perturbations).

- **Gravitational interactions** during inflation $\Rightarrow \mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2} \Rightarrow m_\phi \sim H_{inf} \Rightarrow$ **Massive field**;

- **Quantum fluctuations** for a massive field:

$$|\delta\phi_k| \simeq \frac{H_{inf}}{\sqrt{2k^3}}\left(\frac{k}{aH_{inf}}\right)^{\frac{3}{2}-\nu_\phi}$$

Integrating over all modes $\Longrightarrow$

$$\langle\phi^2\rangle \simeq \frac{1}{3-2\nu_\phi}\left(\frac{H_{inf}}{2\pi}\right)^2$$

$$\nu_\phi = \left(\frac{9}{4} - \frac{m_\phi^2}{{H_{inf}}^2}\right)^{\frac{1}{2}}$$

# Inflation and initial conditions

**What is the minimum field's mass during inflation compatible with observational constraints on CDM isocurvature perturbations?**

Dimensionless isocurvature power spectrum: $\Delta_I^2 \equiv \frac{k^3}{2\pi^2}\left\langle\left(2\frac{\delta\phi}{\phi}\right)^2\right\rangle = (3-2\nu_\phi)\left(\frac{k}{aH_{inf}}\right)^{\frac{3}{2}-\nu_\phi}$

$\beta_{iso}(k_{mid}) = \frac{\Delta_I^2(k_{mid})}{\Delta_{\mathcal{R}}^2(k_{mid}) + \Delta_I^2(k_{mid})} < 0.037$ [Planck Collaboration 2015] $\Rightarrow$ $\nu_\phi \lesssim 1.3 \Rightarrow$ $m_\phi \gtrsim 0.75\, H_{inf}$

Max: $m_\phi \sim H_{inf}$

Min: $m_\phi \sim 0.75\, H_{inf}$

$$\langle\boldsymbol{\phi}^2\rangle = \boldsymbol{\alpha}^2 \boldsymbol{H_{inf}}^2, 0.1 \lesssim \alpha \lesssim 0.25$$

# Inflation and initial conditions

- Field remains overdamped until the EWPT ⇒ $\langle \boldsymbol{\phi}^2 \rangle$ **sets the initial amplitude** for field oscillations in the **post-inflationary era**:

$$\phi_i = \sqrt{\langle \phi^2 \rangle} \simeq \alpha H_{inf}$$

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

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

$$m_\phi \simeq 2 \times 10^{-5} \left(\frac{g_*}{100}\right)^{1/2} \times \begin{cases} \left(\frac{\alpha}{0.25}\right)^{-1} \left(\frac{r}{0.03}\right)^{-\frac{1}{2}} eV\,, & m_\phi > H_{EW}. \\ \left(\frac{\alpha}{0.25}\right)^{-4} \left(\frac{r}{0.03}\right)^{-2} eV, & m_\phi < H_{EW}. \end{cases}$$

# Warped extra-dimension model

- Bulk mass: $M_\Phi^2 = ak^2 + b\sigma''$ $\sigma = k|y|$; $\sigma' = \frac{d\sigma}{dy} = k\, sgn(y)$; $\sigma'' = \frac{d^2\sigma}{d^2y} = 2k\,[\delta(y) - \delta(y-L)]$

- EOM: $\left[e^{2k|y|} g^{\mu\nu}\partial_\mu\partial_\nu + e^{4k|y|}\partial_y\left(e^{-4k|y|}\partial_y\right) - M_\Phi\right]\Phi(x^\mu, y) = 0;$

- Decompose $\Phi$ into **Kaluza-Klein modes**: $\Phi(x^\mu, y) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \phi_n(x^\mu) f_n(y)$;

- The DM field corresponds to the **zero-mode**: $f_0(y) = \sqrt{\frac{2kL(b-1)}{e^{2kL(b-1)}-1}}\, e^{bky}$;

- Particular case: $\boldsymbol{a = b = 0}$ → The bulk scalar is **scale invariant**;

# Warped extra-dimension model

**Do the heavier modes contribute to the DM density?**

$m_n \simeq \left(n + \frac{1}{4}\right)\pi k e^{-kL}$ ⟹ $m_n \sim \mathcal{O}(TeV) \gg m_0$ ⟹ Could lead to an overabundance of DM, if they oscillate with large amplitude after inflation.

**but**

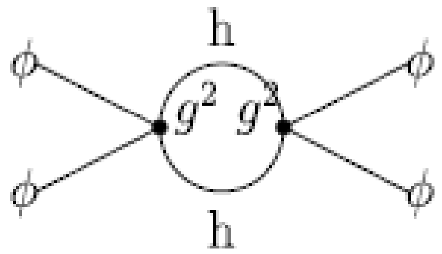
$f_n(L) \simeq e^{kL} f_0(L)$ ⟹ $m_n \gg H_{inf} \Rightarrow$ super-planckian ⟹ Might decay quickly through gravitational coupling.

Only the zero-mode contributes to the present abundance of DM

# Effects of field self-interactions

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

$$\lambda \sim g^4$$




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

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

# Effects of the reheating period

- The mass of DM field vanishes in the radiation era, before the Electroweak symmetry breaking.

**How does the reheating period affect the results?**

- During reheating:

$$\frac{m_\phi^2}{H^2} \sim 3c \frac{V(\chi)}{V(\chi) + \frac{1}{2}\dot{\chi}^2 + \rho_r} \quad \xrightarrow{\frac{V(\chi)}{\rho_r} \ll 1} \quad \frac{m_\phi^2}{H^2} \sim \frac{3}{2} c$$

- There may be a period of inflaton matter-domination:

$$\phi(t) \sim t^\alpha, \qquad \alpha = \frac{1}{2}\left(-1 + \sqrt{1 - \frac{8}{3}c}\right)$$

# Effects of the reheating period

- The interactions between the inflaton and $\phi$ may lead to the production of $\phi$ – particles.

$$\mathcal{L}_{int} = \frac{c}{2}\frac{\phi^2 V(\chi)}{M_{Pl}^2} = \frac{c}{2}\frac{m_\chi^2}{M_{Pl}^2}\chi^2\phi^2 + \cdots \equiv g^2\chi^2\phi^2$$

$$m_\chi^2 = V''(\chi_0) = 3\eta {H_{inf}}^2$$

- $g^2 \sim 10^{-12}\left(\frac{\eta}{0.01}\right)\left(\frac{r}{0.01}\right)$ → Very small coupling.

**Do these particles contribute to the present DM abundance?**

# Effects of the reheating period

- $\phi$-particles never thermalize in the cosmic history $\Rightarrow$ initial amplitude set by $\chi \to \phi\,\phi$;

$$n_{\phi_i} = B_\phi n_\chi = 2B_\phi \frac{\pi^2}{30} g_* \frac{T_R^4}{m_\chi}$$

- Contribution to the present DM abundance:

$$\Omega_{\phi,0} \simeq 0.01 B_\phi \left(\frac{m_\phi}{10^{-5}\ \mathrm{eV}}\right)\left(\frac{T_R}{10^{15}\ \mathrm{GeV}}\right)\left(\frac{m_\chi}{10^{12}\ \mathrm{GeV}}\right)^{-1}$$

$\Rightarrow$ Negligible

**We may neglect the reheating period effects in computing the present DM abundance.**