Scalar field dark matter and the Higgs field

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in collaboration with

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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.

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- 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, ϕ, as DM candidate;
- ϕ 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: $$\ddot{\phi} + 3H\dot{\phi} + m_{\phi}^{2}\,\phi = 0$$

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

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

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

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

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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).

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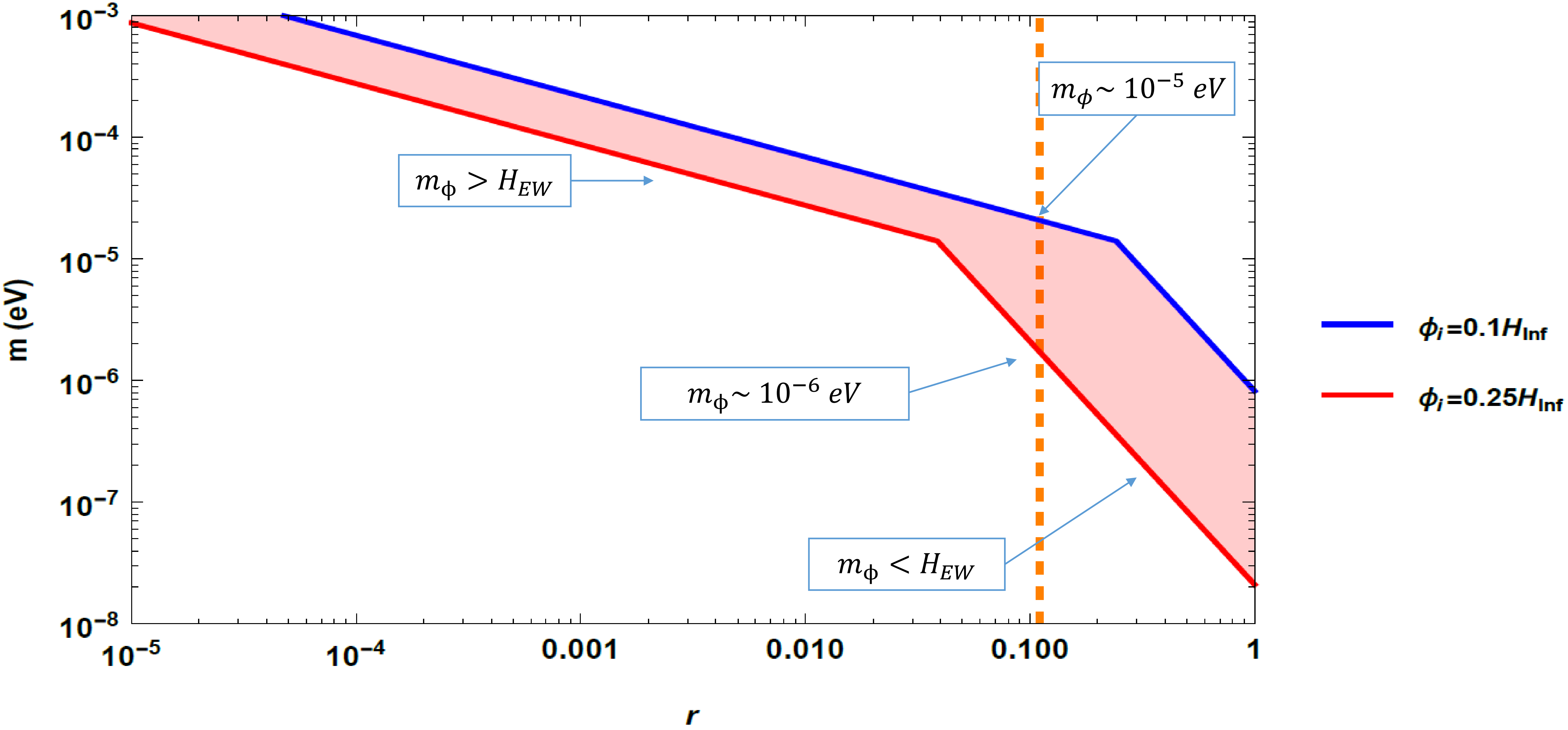
$$r \equiv \frac{\Delta_t^2}{\Delta_{\mathcal{R}}^2}$$

Initial conditions – Results



Non-renormalizable interactions model

Hidden sector
DM field

Visible sector
Higgs boson (and Standard Model fields)

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Heavy messengers,

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Electroweak symmetry breaking

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

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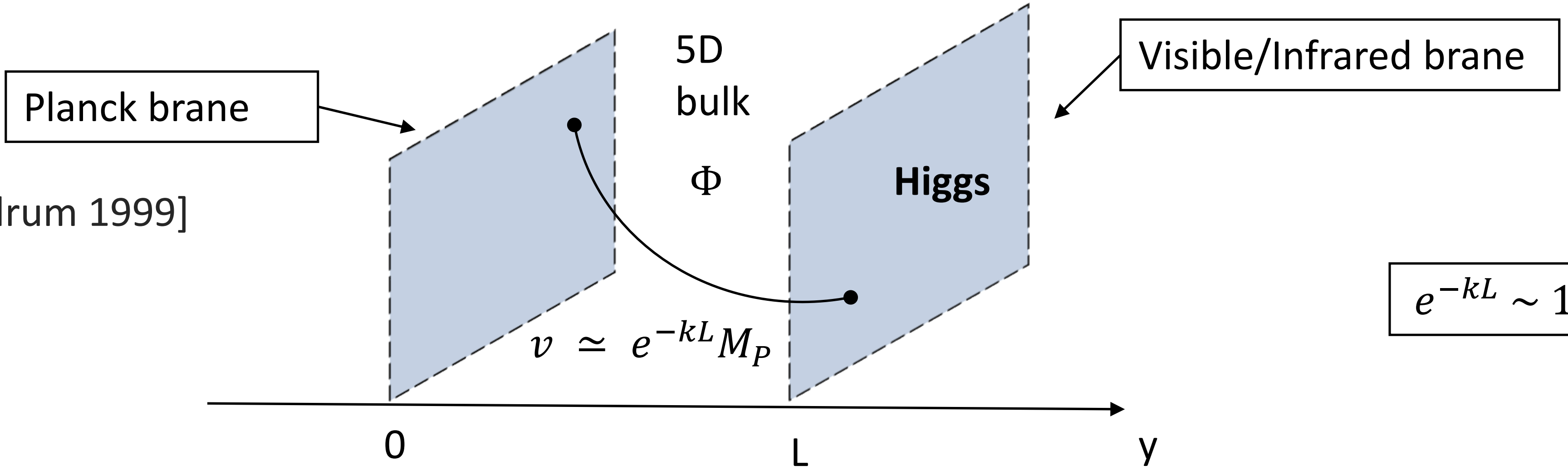
Electroweak symmetry breaking

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

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

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

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

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Mass in the required range.
Interesting hierarchy again:

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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. :

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

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

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- **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 $\Rightarrow$

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

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

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

$\beta_{iso}(k_{mid}) = \frac{\Delta_I^2(k_{mid})}{\Delta_{\mathcal{R}}^2(k_{mid}) + \Delta_I^2(k_{mid})} < 0.037$ [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 $\Rightarrow$ $\langle \phi^2 \rangle$ **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: $M_\Phi^2 = ak^2 + b\sigma''$ $\quad \sigma = k|y|; \quad \sigma' = \frac{d\sigma}{dy} = k\, sgn(\mathrm{y}); \quad \sigma'' = \frac{d^2\sigma}{d^2y} = 2k\,[\delta(y) - \delta(y-L)]$

- 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 Φ 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?

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

but

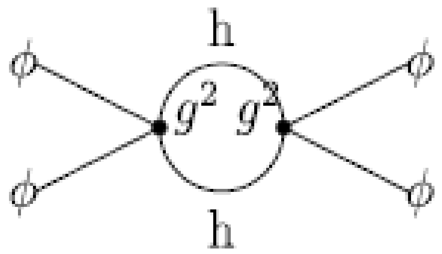
$$f_n(L) \simeq e^{kL} f_0(L) \Rightarrow m_n \gg H_{inf} \Rightarrow \text{super-planckian} \Rightarrow$$ Might decay quickly through gravitational coupling.

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

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

- 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 ϕ may lead to the production of ϕ – particles.

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

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

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

Do these particles contribute to the present DM abundance?

Effects of the reheating period

- ϕ-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.