Cosmological phase transitions in a dimensionally-reduced vector dark matter model

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Abstract

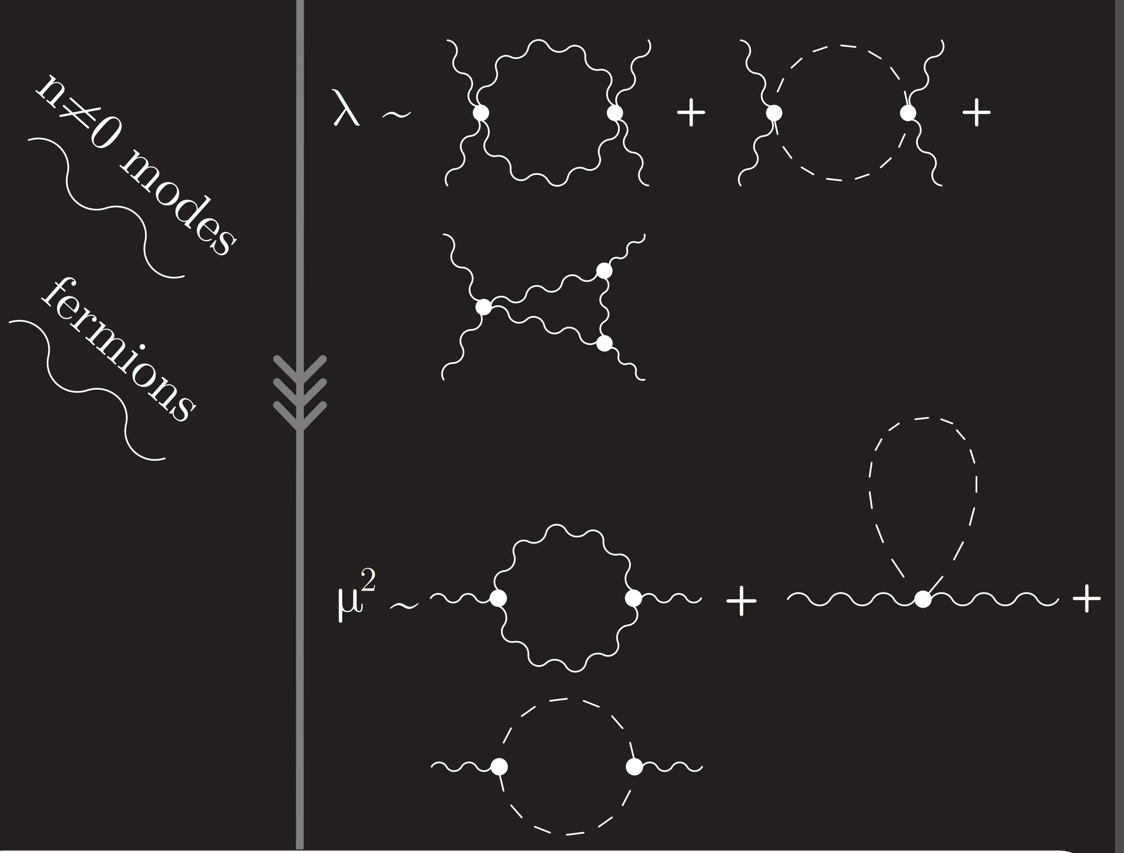
We explore potential gravitational signatures originating from a non-abelian vector dark matter framework, where interactions with the visible sector are mediated via a dark vector-like fermion. We examine the impact of the dark fermion on the phase transition and contrast it with a scenario involving a pure scalar-vector theory. To this effect, we have constructed a dimensionally reduced effective field theory, which has been shown to help mitigate troublesome uncertainties such as nonphysical renormalisation scale and gauge dependence.

Dimensional reduction

4D Hard Theory (T = 0)

$$\mathcal{L}_{4D} = -\frac{1}{4}|F^a_{\mu\nu}|^2 + |D_\mu\phi|^2 + \mu^2|\phi|^2 + \lambda|\phi|^4$$

D=4
Λ ~ πT



3D Soft Theory (m/T < 1)

$$\mathcal{L}_S = -\frac{1}{4}|\mathcal{F}^a_{ij}|^2 + |D_i\mathcal{F}_0|^2 + |D_i\varphi|^2 + m_D^2|\mathcal{F}_0|^2 + \mu_3^2|\varphi|^2 + \lambda_3|\varphi|^4 + \lambda_V|\varphi|^2|\mathcal{F}_0|^2 + \lambda_T|\mathcal{F}_0|^4$$

D=3
Λ ~ gT

Temporal scalars

3D Ultra-Soft Theory (m/T < 1)

$$\mathcal{L}_{US} = -\frac{1}{4}|\bar{\mathcal{F}}^a_{ij}|^2 + |D_i\bar{\varphi}|^2 + \bar{\mu}_3^2|\varphi|^2 + \bar{\lambda}_3|\bar{\varphi}|^4$$

D=3
Λ ~ g²T

Models

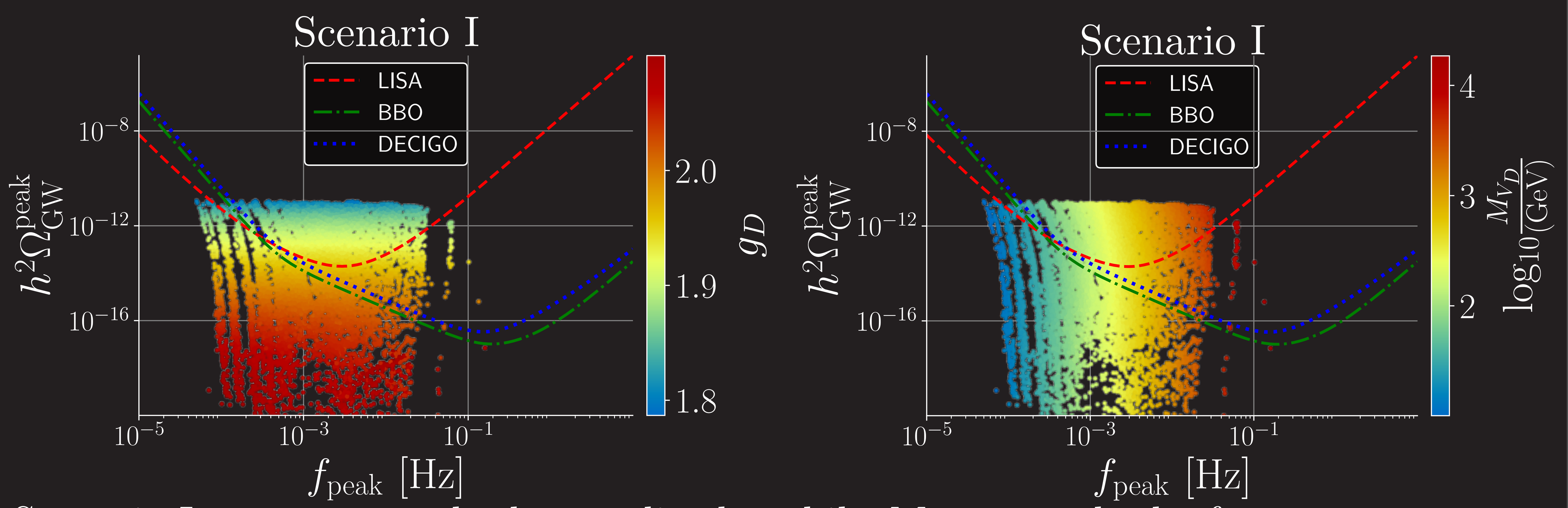
$$\mathcal{L}_{\text{S-I}} = -\frac{1}{4}(V^a_{\mu\nu})^2 + |D\mu\Phi_D|^2 - \mu_D^2\Phi_D^\dagger\Phi_D - \lambda_D(\Phi_D^\dagger\Phi_D)^2$$

→ **Model parameters:** M_{V_D}, M_{H_D} and g_D

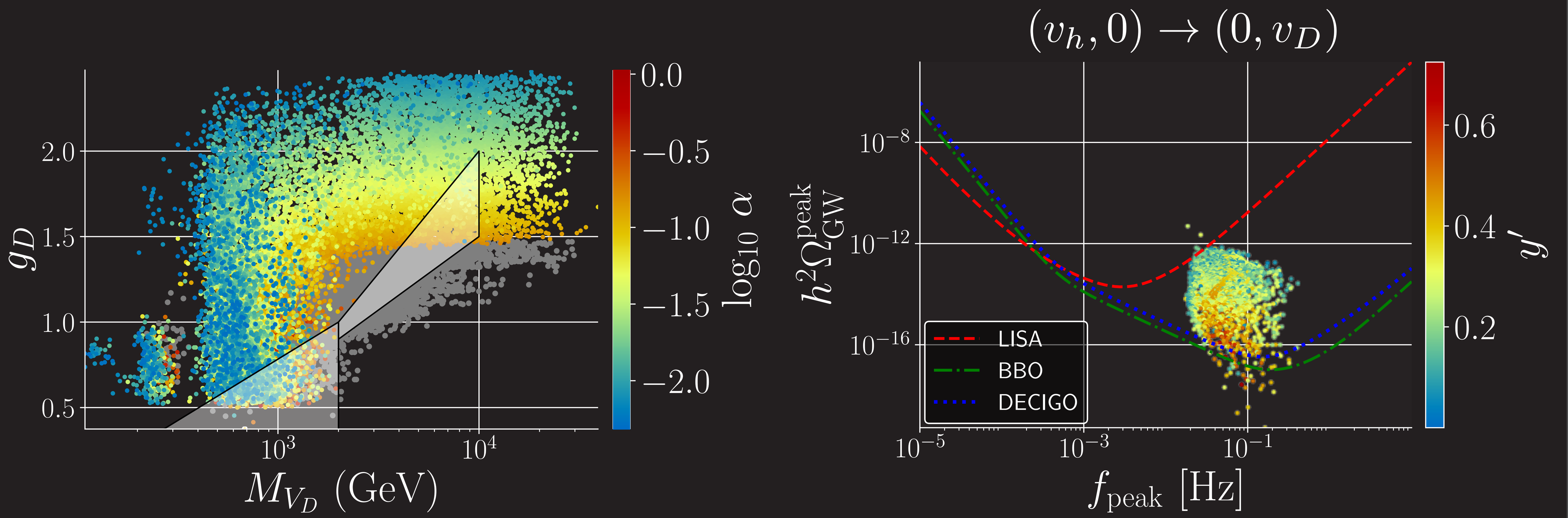
$$\mathcal{L}_{\text{S-II}} = \mathcal{L}_{\text{S-I}} - \frac{1}{4}(V^i_{\mu\nu})^2|_{B,W^i,G^i} + \bar{f}^{\text{SM}} i \not{D} f^{\text{SM}} + |D_\mu\Phi_H|^2 - \mu_H^2|\Phi_H|^2 - \lambda_H|\Phi_H|^4 - \lambda_{HD}|\Phi_H|^2|\Phi_D|^2 - (y\bar{f}_L^{\text{SM}}\Phi_H f_R^{\text{SM}} + y'\bar{\Psi}_L\Phi_D f_R^{\text{SM}} + \text{H.c.})$$

→ **Model parameters:** M_{V_D}, M_{H_D} and g_D, m_{f_D}, m_F (physical Ψ mass), $\sin\theta_S$ (scalar mixing angle)

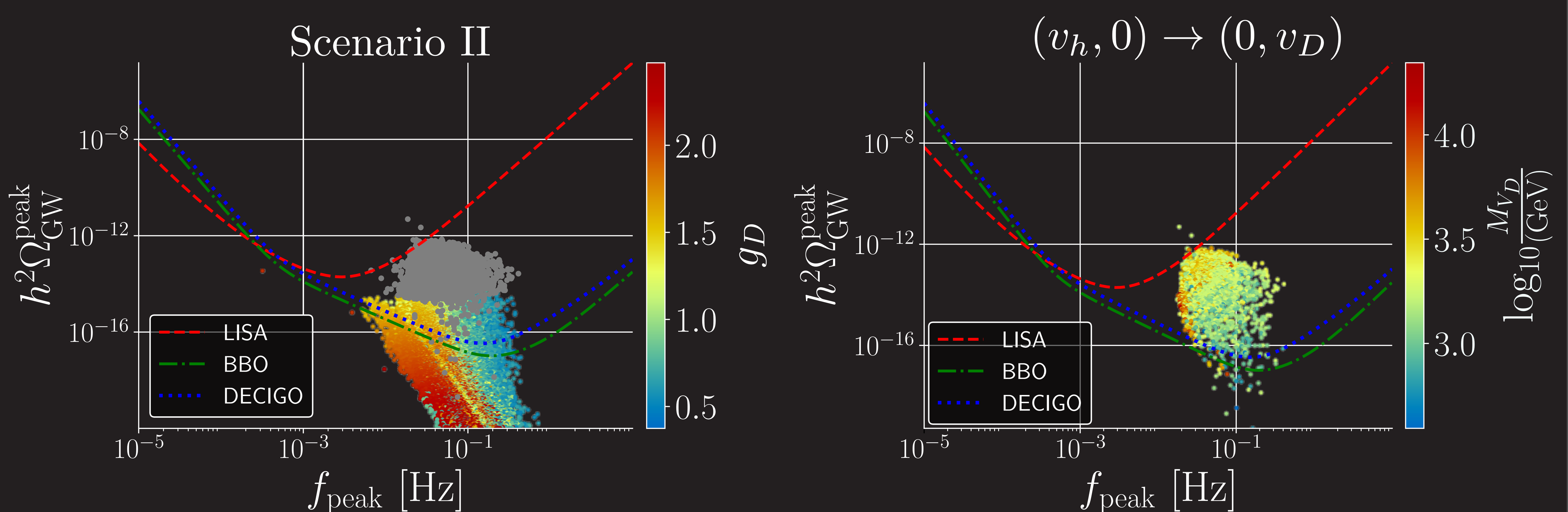
Numerical results



Scenario I: → g_D controls the amplitude, while M_{V_D} controls the frequency.



→ Scenario II: similar behaviour with g_D. y' leads to weaker transitions. High-T expansion breaks down ($m(\phi)/T > 1$) for stronger transitions in scenario II.



→ M_{V_D} controls the frequency in qualitative opposite behaviour between scenario I and II.

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