Electroweak Phase Transitions in a Vector Dark Matter Scenario

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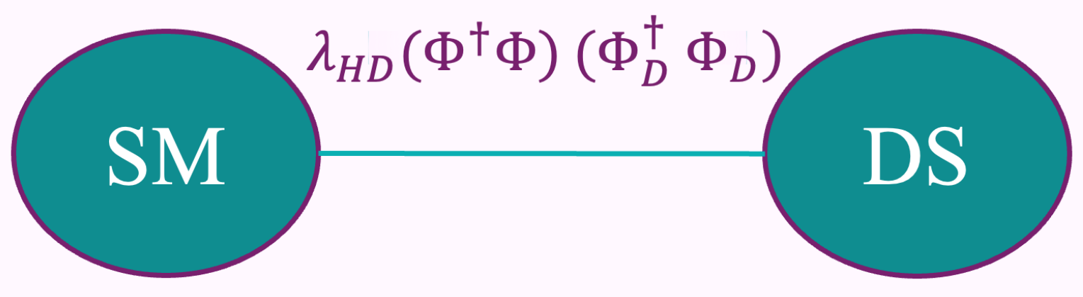
Abstract

This research investigates the consequences of first-order phase transitions (FOPT) in the early Universe, specifically in an extension of the Standard Model (SM) that include a vector dark matter (DM) candidate. The study focuses on a scenario based on a dark *SU(2)* group and provides a case study for assessing the sensitivity of future gravitational wave signals from phase transitions in connection with the phenomenology of dark matter. To ensure consistency with experimental results, constraints are applied to the parameter space of the model.

Introduction

- Cosmological and astrophysical observations strongly indicate that baryons are not the dominant constituent of matter in the Universe, in contrast to ordinary substances found on Earth. This non-baryonic matter, referred to as DM, is deemed "dark" due to its weak interactions with SM particles. There are two most crucial properties of any DM candidate:
  1. Its weak interaction strength with SM particles
  2. Its stability on cosmological timescales
- These models can be constrained by direct and indirect detection experiments and by the LHC, and the relative importance of such constraints depends on the hypotheses about the interactions of DM with SM particles. Models where the DM interacts exclusively through the Higgs boson are in general less constrained.
- Gravitational waves (GWs) offer a new complementary approach to investigate the models that are directly coupled with the Higgs. This is because they typically require the existence of additional scalar fields that can potentially trigger a first-order phase transition (PT) in the Early Universe, leading to the emission of GWs. This is the focus of the present study.
- To motivate a specific choice for the DM model, we rely on the portal through which our DM model is coupled to the SM.
- We considered the standard freeze-out regime for the production of DM relic density.



Interaction between Standard Model (SM) and Dark Sector (DS)

The Model

- We consider an extension of the SM with a $SU(2)_D$ gauge symmetry under which all the SM particles are singlets.
- We introduce a scalar doublet that breaks the $SU(2)_D$ symmetry via a Higgs mechanism in the dark sector. The custodial SO(3) symmetry in the $W^\mu_{1,2,3}$ component space ensures that three spin-one particles are stable and mass-degenerate with a common mass $m_{VD} = g_D\, v_D/2$, where g_D is the $SU(2)_D$ gauge coupling. Because all other particles are SO(3) singlets, custodial symmetry prevents the decay of the gauge bosons.
- The Lagrangian of the model is

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}(F_D^{\mu\nu})^2 + (\mathcal{D}\Phi_D)^\dagger\,(\mathcal{D}\Phi_D) + \mu_D^2\Phi_D^\dagger\Phi_D - \lambda_D\left(\Phi_D^\dagger\Phi_D\right)^2 - \lambda_{HD}(\Phi_D^\dagger\Phi_D)(\Phi^\dagger\Phi)$$

- After EW and dark symmetries breaking, we write the scalar doublet in the unitary gauge as

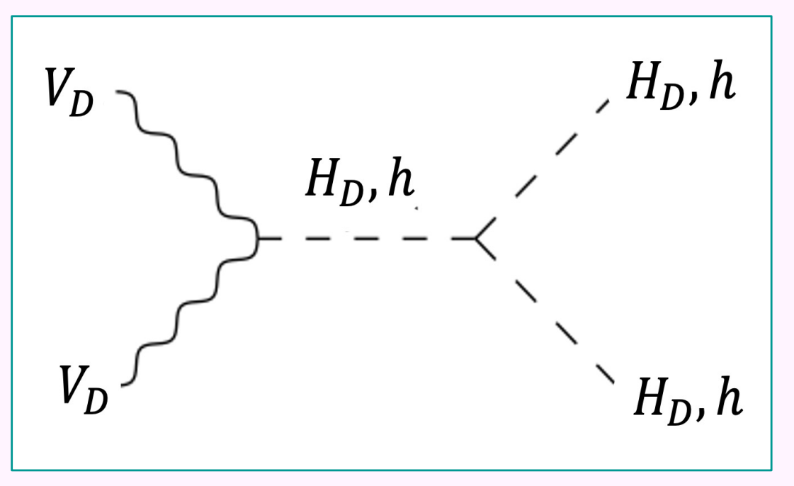
$$\Phi_H = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h_1\end{pmatrix}\ ,\quad \Phi_D = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_D+h_2\end{pmatrix}$$

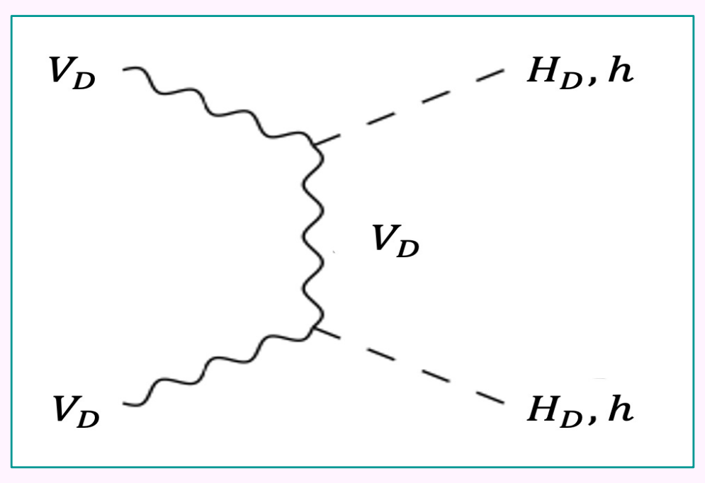
  where v and v_D are VEVs of EW and $SU(2)_D$ symmetries respectively. In addition, h_1 and h_2 are real scalar fields in the interaction eigenbasis.
- The portal coupling λ_{HD} between the SM and the dark sector induces a mixing between the two scalar fields h and h_D.
- The free parameters of the model are: the mass of the dark matter m_{V_D}, the mass of dark Higgs boson m_{H_D}, the dark gauge coupling g_D and the mixing angle θ.

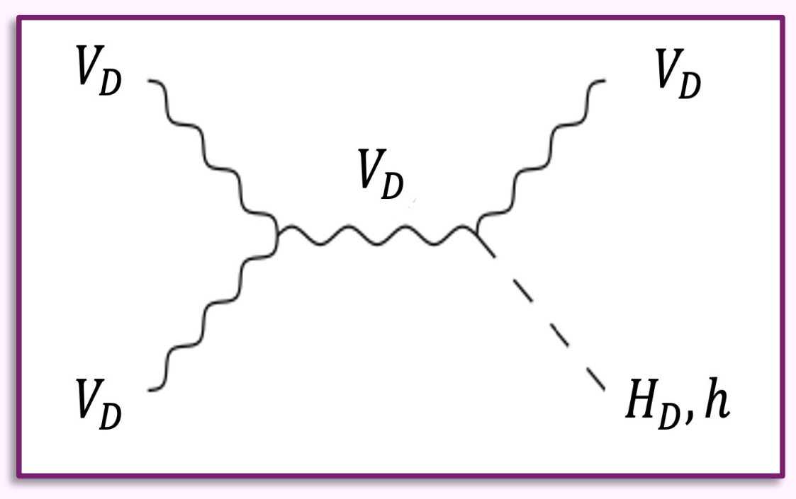
Constraints

- Theoretical constrainsts (perturbative unitarity / boundness from below)
- Collider constraints: bounds from direct searches for scalar particles, as well as the compatibility of the predictions of the Higgs couplings modification in our model with the corresponding measurements at the LHC.
- Electro-weak precision tests
- DM relic density (PLANCK) : $\Omega_{DM} \sim 0.1\,\frac{x_f}{\sqrt{g_*(m_{VD})}}\,\frac{10^{-8}GeV^{-2}}{<\sigma v>} \approx 0.12$

  $< \sigma v > \equiv$ thermally average annihilation cross section
- Some examples of DM annihilation diagrams are:



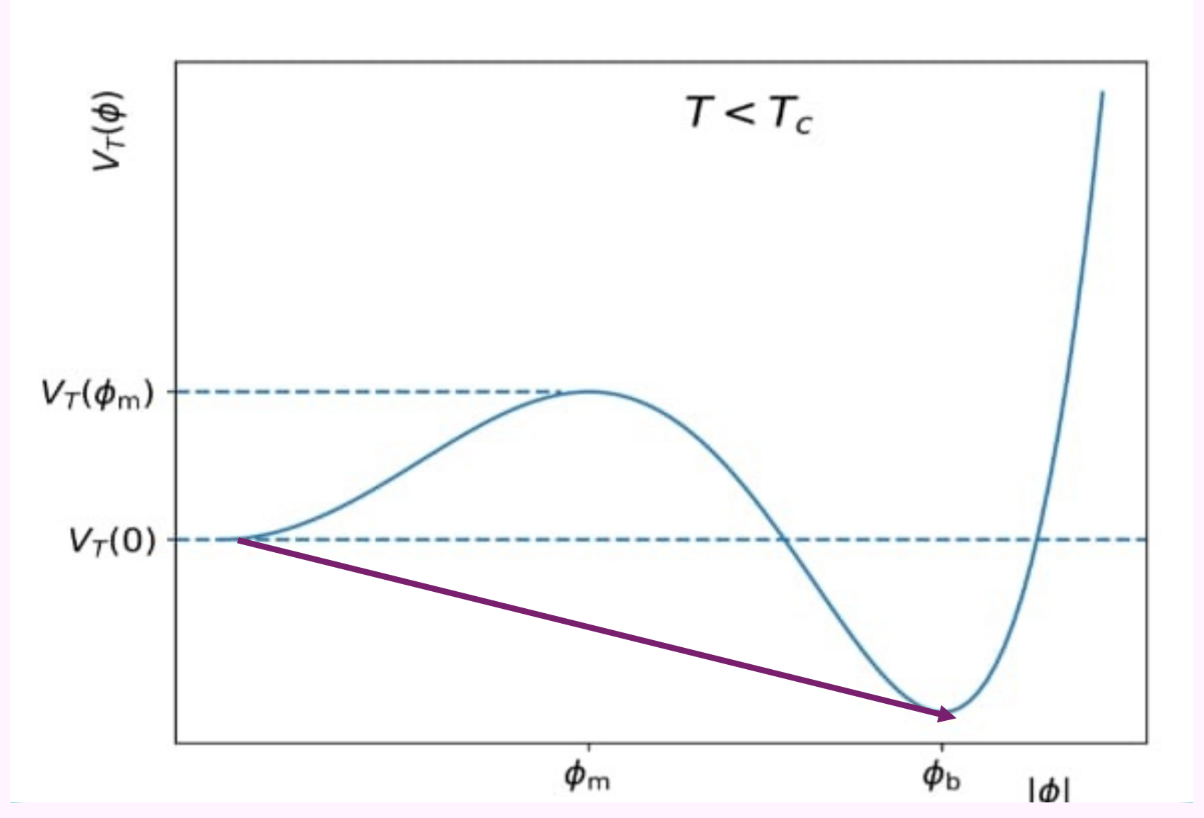




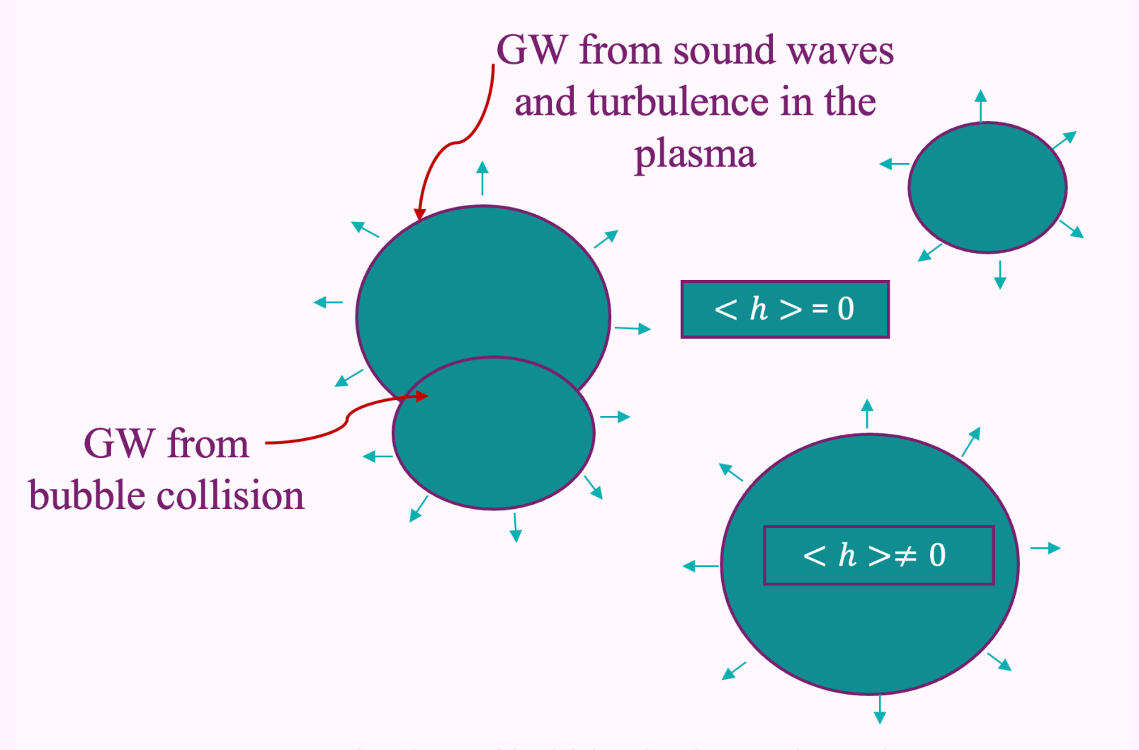
- *The annihilation channel on the right exhibits a unique characteristic because it involves one DM particle in the final state, which is not possible with ordinary models based on a Z_2 symmetry.*
- DM direct detection (XENON1T / LUX-Zepelin)
- DM indirect detection (HESS / FERMI LAT)

Gravitational Waves from First-Order Phase Transition

- In a FOPT, the system goes from a metastable state to the ground state through a process of bubble nucleation. Such bubbles expand and then fill in all the space.
- When bubbles expand and collide with each other, they release a huge amount of energy which is in part converted into a background of gravitational waves.
- The evolution of the system can be well described by its potential or, equivalently, by its free energy as a function of the order parameter describing the transition.



The effective potential $V_T(\phi)$in a FOPT

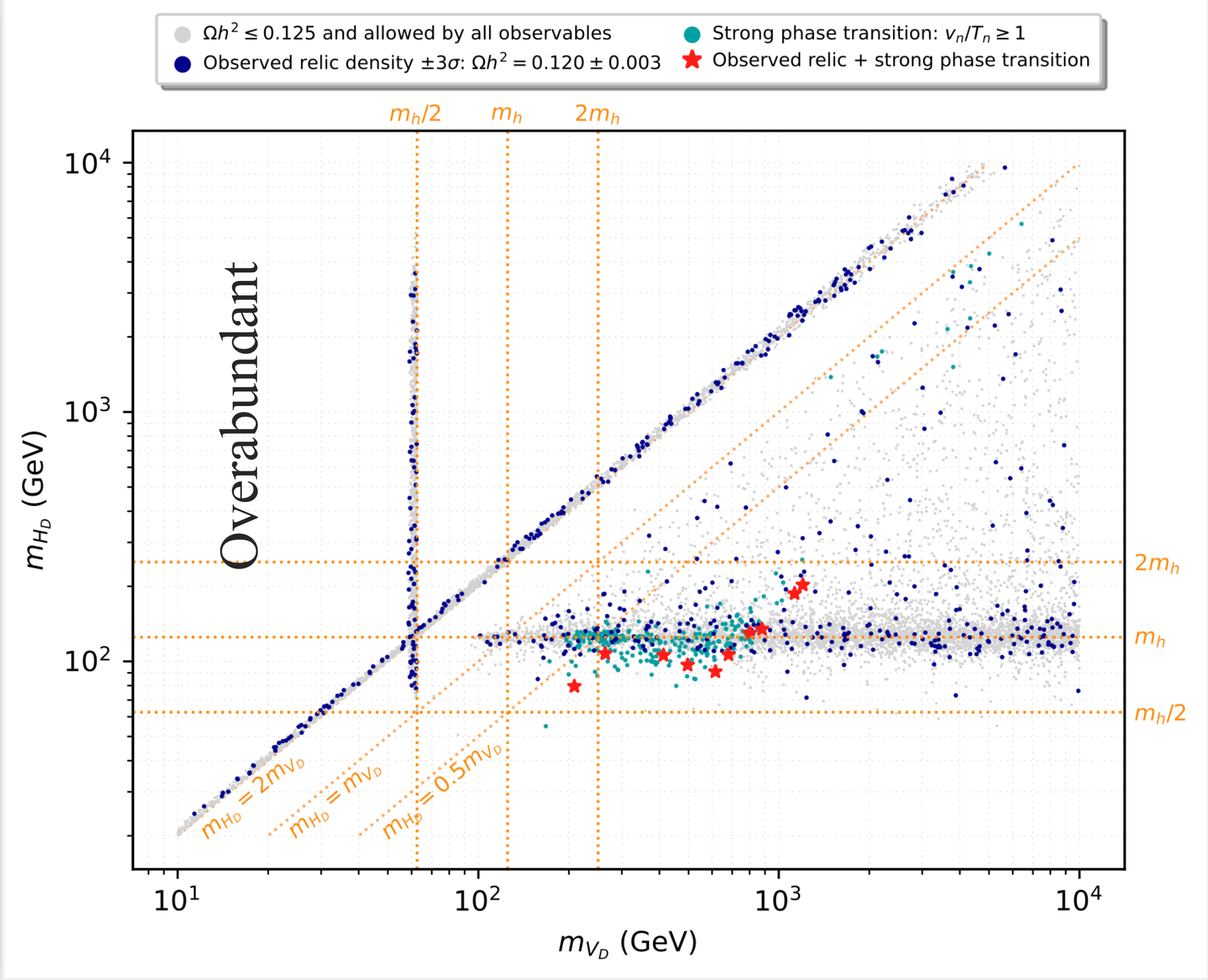


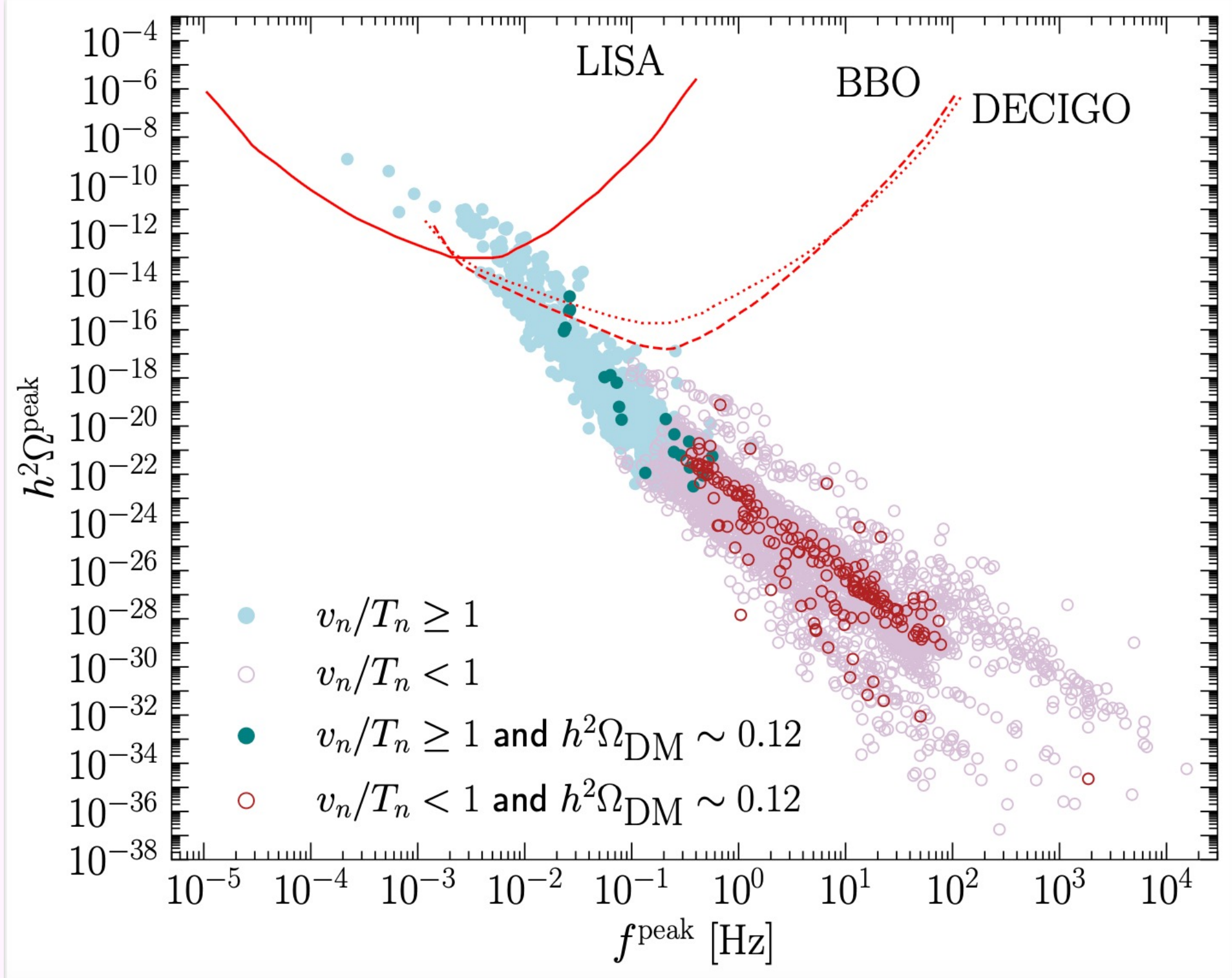
Nucleation of bubbles in the Early Universe

- The gravitational wave power spectrum is characterised by the following phase transition parameters (can be computed from the Lagrangian of a specific model):
- α: Strength of the phase transition
- β/H: Inverse time duration
- T_P: Percolation temperature
- v_w: Bubble wall speed

The complementary relation between dark matter and gravitational waves

- $m_{H_D} = 2m_{V_D}$: annihilation proceeds through H_D resonance.
- $m_h = 2m_{V_D}$: annihilation proceeds through h resonance.
- The lower triangular region (below $m_{V_D} = m_{H_D}$ and above $m_{H_D} = \frac{m_h}{2}$) is non-resonant but all other contributions are allowed.
- The region with the higher density of points where $m_{H_D} \simeq m_h$ and $m_{V_D} > m_h$, is less constrained by collider observables.





- GW signal $h^2\Omega^{peak}$ is shown as a function of the peak frequency f^{peak}.
- The colour code is associated to the strength of PT and the relic density of DM.
- $\frac{v_n}{T_n} \geq 1 \rightarrow$ strong PT
- $\frac{v_n}{T_n} < 1 \rightarrow$ weak PT
- The sensitivity curves of future gravitational wave detectors are also shown.

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