PhD Work Project
Imprints of Dark Sectors from the Early Universe

PhD Student: Tommaso Sassi
tommaso.sassi@unifi.it

Advisor: Andrea Tesi
andrea.tesi@fi.infn.it

Two of the most intriguing mysteries of our current understanding of fundamental physics and cosmology are the nature of Dark Matter (DM) and the origin of cosmic inflation. These two aspects can be investigated in terms of models of new physics (beyond the Standard Model) that explain the origin of DM and predicts new imprints on cosmologically large scales.
During the PhD project, the main focus will be on the so-called Dark Sectors (DS): new particle physics sectors that host a DM candidate as well as additional new particles and interactions. Particularly attractive and elegant scenarios are dark sectors secluded from the Standard Model (SM), i.e. models where the new sector is a total singlet under the SM gauge interactions. In such a case, the interactions of the DS with us are then just gravitational or mediated by contact interactions possibly suppressed by a high scale in an Effective Field Theory (EFT) description.
Concretely, we explore new physics scenarios that generate the dark matter of the universe and leave their imprints in cosmological observables such as the CMB, the matter power spectrum and gravitational waves. We aim at studying the dark sector production during the period of cosmic inflation and standard Big Bang cosmology, their experimental signatures in cosmological observations and laboratory experiments.
Among the possible scenarios interesting dynamical mechanisms for the generation of Dark Matter are (first order) phase transitions during inflation or during standard cosmology. These mechanisms are also tightly connected with the dynamics associated to the end of inflation and the reheating process of the universe, which will be also a target of our study.

Based on this scenario, we plan to touch upon the following topics during the PhD program:

- **Non-thermal Dark Matter production**: If DM is one of the states in the DS, it will behave as a total singlet under the SM and we expect all the standard thermal production mechanisms such as the 'freeze-out' to not be effective. In this case, dark matter has to be produced non-thermally, and one of the most elegant non-thermal mechanism is gravitational particle production during inflation. It exploits the time-dependence of the metric tensor in FRW cosmology to produce particles from the non-adiabatic evolution of free fields in curved space (it is the mechanism at the earth of the generation of inflationary primordial perturbations).
  Depending on the model it can produce features on the dark matter power spectrum

at small scales, modifying the prediction of ΛCDM model. Notably this has been discussed in recent years for the case of dark photon dark matter.
The shape of the matter power spectrum depends on how particle production starts during inflation and we will classify the possibilities and they related phenomenological consequences.

- **Cosmological imprints: phase transitions**: Cosmological first order phase transitions are an active field of research. They received a lot of attention in recent years since they can produce an observable spectrum of gravitational waves (GWs) testable at current and future interferometers. Our focus will be on phase transition associated to the production of DM, which is typically the lightest stable state of the low-energy phase. We plan to study the impact of phase transition on the cosmological perturbations tested by CMB and large scale structures, focusing on dynamics happening during inflation and during the standard Big Bang cosmology (radiation domination). In the first case, the phase transition alters the predictions for the scalar and tensor (GWs) perturbations: based on simple scalar field models we would like to characterize the amplitude and shape of the primordial power spectra, that are later fed into the CMB and matter power spectrum. In the second case, a phase transition alters the equation of state of the universe leading to modifications of the growth of sub-horizon dark matter cosmological perturbations.
  First order phase transitions during radiation domination are also extremely interesting when they are associated with some degree of 'supercooling'. In such a case, the nucleation temperature is much below the critical temperature leading to a cooling phase of the universe. This is associated to high frequency and large amplitudes in the emitted GWs spectrum. Building upon existing works we would like to assess more in general what are the conditions for supercooled phase transitions in the context of DS described by approximate thermal conformal field theories (CFTs).
- **Dark Matter searches**: In the context of DM coupled to us via contact interactions, we would like to analyze the phenomenological consequences in terms of a DM EFT scenario.
  Concretely, we plan to focus on (complex) dark photon dark matter, a vector DM candidate, interacting through a set of (non redundant) dimension six operators constructed with DM and SM fields. Since DM is a gauge singlet under the SM, the SM appears as a singlet operators (of possibly any tensor structure), and we aim at characterize the parameter space relevant for direct (DD), indirect (ID) detection and collider searches.
  We would also search for possible UV-completions of our phenomenological EFT.