OBSERVATIONAL TESTS OF A DARK SECTOR

Executive summary

The existence of dark matter suggests the presence of an extended dark sector that is neutral under all standard-model forces. This hidden sector could be extremely simple and minimal but it might as well conceal a rich and intricate structure with matter and forces of its own. The search of observational tests of the dark sector is a new and rapidly expanding field of research. It offers new insights on the long-standing problem of DM and the role played by it in cosmology and structure formation. Experimental tests are already being deployed, and more will be in the near future. The participants of this proposal have already contributed to the identification and the study of some of these tests. To proceed further in this line of enquire, it is necessary to coordinate the ongoing efforts of the many players in the field. As they belong to different communities (particle physics, astrophysics and cosmology), they can be brought together most effectively by the development of this proposal at the IFPU in agreement with the Institute's aim of providing a place for researchers to gather and work together on common research interests in fundamental physics.

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Motivations

About one-fourth of the energy balance of the Universe today is in the form of dark matter (DM). This well-established evidence, however, comes with an double-edged consequence: the same overwhelming evidence that assures us that DM exists, make it hard to detect. DM appears to be some new kind of particle that has mass, and that is, therefore, subject to gravity. Gravitational interactions are indeed those that let us know where DM is but give us no handle on what it is made of. Interactions of DM particles with ordinary matter in the Standard Model (SM) would help us in clarifying its nature but they seem to be so feeble that escaped, so far, the net of all detection experiments. The existence of DM thus suggests the presence of a *dark sector* that is neutral under all SM forces. This hidden sector could be extremely simple and minimal but it might as well conceal a rich and intricate structure with matter and forces of its own.

If one tries to organize a strategy to test the existence and composition of a dark sector, there emerges immediately a clear conceptual difference with respect to the case of a weakly interacting massive particle (WIMP). The WIMP model is nowadays severely challenged by null results of both direct and indirect detection experiments for the very same reason that made it so appealing and popular: By identifying the DM particle with a thermal relic of the early Universe with weak interactions and a mass around the electroweak scale, it suggested exactly where to look for. On the contrary, exploring a generic dark sectorcould easily turn into a hopeless endeavour without an organizing principle in mind.

On this basis, it is conceivable to start classifying possible connections, dubbed *portals*, with the visible world through which the dark sector manifests itself (in addition to gravitational effects). Using the language of effective operators as an organizing principle, we schematically have

$$\mathcal{L}_{\rm SM/DS} = \mathcal{O}_4 + \frac{1}{\Lambda}\mathcal{O}_5 + \frac{1}{\Lambda^2}\mathcal{O}_6 + \dots \ , \tag{1}$$

where the operators are grouped by increasing dimension, and the dimensionful quantity Λ is a scale that defines and controls the strength of the effective interaction. In particular, we shall focus on the following possibilities:

- *Vector portal*

  Allowing interactions within constituents of the dark sectorseems natural enough. The simplest possibility is a $U(1)$ gauge interaction within the dark sector—modelled as a dark analog of electromagnetism and thus contemplating the existence of a dark photon—under which all states in the dark sectorare charged. The $U(1)$ local symmetry in the dark sectorcan be either spontaneously broken—by means of a dark analog of the Higgs mechanism—or unbroken. In the former case the dark photon is massive, and it interacts with the SM particles via an unavoidable mixing ϵ with the ordinary photon, $\mathcal{L}_{\rm SM/DS} = \epsilon\, F_{\mu\nu}B^{\mu\nu}$, with F the electromagnetic field strength and B the field strength associated with the dark photon field. This is an example of a dimension-four portal interaction in eq. (1). If the $U(1)$ symmetry is unbroken, on the contrary, the dark photon remains massless, and fully decoupled from the SM sector. In such case, the massless dark photon could only interact with the SM sector through higher-dimensional operators generated by the exchange, if any, of heavy messenger fields communicating between the two sectors. In the language of eq. (1), the leading interactions of the dark photon with SM fields are given in this case by dimension-six operators generating electric and magnetic dipole moments for SM fermions.

- *Pseudo-scalar portal*

  Axion-like particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries, and they populate many high-energy extensions of the SM. Among them, the most compelling case is that of the QCD axion, whose existence guarantees a natural solution of the strong CP problem. At the same time, ALPs are a potentially good candidate for DM since they elegantly explain the abundance of DM that we observe today by means of the so-called misalignment mechanism. A portal with the visible sector is often identified with the coupling of the axion a with the charge-parity violating term $F_{\mu\nu}\tilde{F}^{\mu\nu}$, with $\tilde{F}$ the dual of the field strength F. In eq. (1), this is the typical example of a dimension-five portal interaction, $\mathcal{L}_{\rm SM/DS} = (a/f)F_{\mu\nu}\tilde{F}^{\mu\nu}$, with the scale Λ identified with f, the axion decay constant.

- *Neutrino portal*

  SM neutrinos are, in principle, legitimate DM candidate since they are neutral and stable. However, they can not compose all of the observed DM because of the smallness of their mass and the magnitude of their coupling. One obvious solution is to postulate the existence of heavier *sterile* neutrinos with weaker interactions that fulfil the constraints from cosmic structure formation and phase space densities. A sterile neutrino is a good DM candidate if its mass is in the kilo-eV range. Sterile neutrinos could provide a link between the SM particles and the dark sector, besides generating active neutrino masses via the celebrated seesaw mechanism. This is another example of a dimension-four portal, given schematically by $\mathcal{L}_{\rm SM/DS} = y\bar{L}\tilde{H}N + h.c.$, with L the left-handed lepton doublet, $\tilde{H}$ the conjugate of the Higgs field, N the sterile neutrino, and y a Yukawa coupling.

For completeness, we also mention the so-called *Higgs portal* in which the leading operator would be in the form $(\mu\phi + \lambda\phi^2)H^\dagger H$, where H is the Higgs field and ϕ a generic scalar state of the dark sector. We do not include this possibility in the present proposal because it is, in general, less definite (one can add several scalar fields and these also to higher-order operators) and of dubious theoretical motivation (scalar fields other than Goldstone modes are always problematic because of their peculiarity of non-decoupling from UV physics).

The aim of this research project is to **propose and explore observational tests of the dark sector** focusing on the aforementioned dark sectorportal directions, and by following as much as possible new unexplored lines of investigations. In particular, covering the possibility that this new sector be truly dark and interacting with ordinary matter only gravitationally.

Listening to space-time

We explore possible signatures from the dark sector in gravitational waves. The first direct observation of gravitational waves from two merging black holes [1] and neutron stars [2] opened the doors to a new way of doing astrophysics. The avenue we would like to explore is the following. If two neutron stars are macroscopically charged under a new force the inspiral dynamics changes with respect to the standard prediction of general relativity because of two main effects: *i)* a new contribution adds to the gravitational potential thus altering the strength of gravity and *ii)* the binary system—assuming different charge-to-mass ratios for the two stars—loses energy because of the presence of dark dipole radiation in addition to the usual quadrupole term in general relativity. The precision of the measurement of the inspiral dynamics by gravitational wave interferometers is already such as to place meaningful constraints on the relative strength of the new force compared to gravity. This situation has been explored in recent publications that mostly focused on the possibility of a massive force carrier [3–6]. The main obstruction to the validity of this qualitative picture is the assumption of having a neutron star macroscopically charged. Addressing this point requires both a microscopic and macroscopic perspective. At the microscopic level, one should provide a mechanism to explain the presence of dark sector particles inside a neutron star. At the macroscopic level, the challenge is to find equilibrium solutions of Einstein-Maxwell field equations that are compatible with the observed properties of neutron stars (as far as mass, radius and tidal deformability are concerned) and that, at the same time, generate a net macroscopic charge.

The age of gravitational wave astronomy has just started and, in light of the tremendous amount of data that is expected in the next years, we must leave no stone unturned in our quest for new phenomena beyond the current knowledge of general relativity, particle physics and nuclear physics. In this respect, the physics-case proposed in this research project provides a clear example of an observational test of the dark sector that requires an interplay between these—apparently unrelated but in reality complementarily linked—fields of research.

Darkness out of light

We explore possible signatures from the dark sector in the tail of the Cosmic Microwave Background (CMB) radiation. The intensity of the CMB, measured by the FIRAS instrument onboard of the COBE satellite, is in perfect agreement with a black-body spectrum at temperature $T = 2.725$ K. Experimental data, however, only cover a limited range of frequencies around the peak of the spectrum. At frequencies $\omega \ll T$, within the so-called Rayleigh-Jeans tail of the Planck's distribution function, there is considerable room for modifications. As discussed in ref. [7], it is possible to construct explicit dark sector models that give an order one (or larger) increase of photon count in the Rayleigh-Jeans tail which can be tested by existing and upcoming experiments aiming to detect the cosmological 21 cm emission/absorption signal. One of the most important eras in cosmic evolution is marked by the formation of the first luminous objects and the associated transition of the Universe from a neutral to ionized phase. Observations of the cosmological 21 cm emission/absorption signal offer the potential of opening a new window into this epoch. The EDGES experiment recently presented a tentative detection of 21 cm absorption coming from the interval of redshifts $z = 15$-20 [8]. The amount of absorption does not agree with standard cosmological expectations, and seems to indicate a photon count in the Rayleigh-Jeans tail of the CMB higher than expected. If confirmed, this result could be the first evidence for the existence of a dark sector. The work of ref. [7] can be extended in various directions. As far as the structure of the dark sector is concerned, for instance, it is important to understand which class of models has the possibility to incorporate the minimal requirements that are needed to sizably change the 21 cm emission/absorption signal. On the cosmological side, an accurate and comprehensive description of the Universe at the end of the dark age remains a challenging task mostly because of large astrophysical uncertainties affecting the process of star formation. Understanding and reducing these uncertainties will definitely play a crucial role for the correct interpretation of any future experimental result.

Particle physics signatures

The portal coupling of the dark sector can manifest itself in high-energy experiments by means of processes where some (or even all) of the energy goes missing or in precision experiments where the value of observables that are known with high precision is modified. If the portal interaction contains also operators coupling SM states of different flavors, they could be probed in flavor-physics experiments. Finally, fermion states in the dark sector can be identified in a natural manner with sterile neutrinos. They can take part in oscillations, contribute to the interpretation of neutrino experiments and be searched directly as heavy neutrino states.

Different experimental areas in particle physics provide promising tests for the presence of the dark sector:

- Searches for axions and ALP (including massive dark photons): laser experiments ("shining light through a wall"), DM conversion (via the Primakov process) in microwave cavities ("haloscopes") or photon conversion in the sun ("helioscopes");
- Collider experiments: electron and proton beam-dump experiments (in which dark photons are emitted by *bremsstrahlung*) as well as missing energy events (in which one or more final states are dark photons) at the LHC and future colliders [9,10];
- Decays of neutral states: experiments for neutron, rare Kaon and B-meson decays into final states some (of even all) of which are invisible. These can be dark photons or part of the dark-sector matter states [11,12];
- Neutrino oscillations and searches for heavy neutrinos;
- Precision measurements: limits on anomalous magnetic and electric dipole moments as well as atomic physics experiments (atomic clocks and other high-precision measurements of atomic energy levels).

Many of the above searches are already under way in current or proposed experiments (see [13] and [14] for reviews of the relevant experiments and conceptual frameworks). This proposal would like to study the possibility of refining the observables to be searched for by a dedicated study of the dark sector. In addition, the identification of novel signatures in similar or even new experimental setups would also be of great interest. For the latter, the interplay between astrophysical and cosmological observables and particle-physics signatures might play an important role.

Dark matter properties

Within the dark sector, DM enjoys new properties not searched for in the case of the WIMP paradigm. Beside being made of more than one component, it can have self-interactions, usually parameterized in terms of a $U(1)$ gauge symmetry carried by dark photons (possibly broken and with the dark photons becoming massive). Such a richer model of DM lends itself to many observational tests. Among these, we mention

- those from the (mostly) collisionless dynamics of DM in the galaxy (covering bounds on galaxy collisions like from the Bullet Cluster [15] to the ellipticity of the DM halo mass distribution);
- those on the flattened DM mass distribution (dark disk) [16] which are suggested by the possibility of DM forming bound states (like atoms for ordinary matter) and therefore being partially thermalized like baryonic matter;
- novel direct and indirect detection cross sections due to the long-range force (to be contrasted to the contact interaction of WIMPS) and the possible milli-charge carried by DM [17];
- different computation of the relic abundance: multi-component DM requires coupled Boltzmann equations with new decay channels. In addition, Sommerfeld factors are enhanced by the dark force and might modify in a significant manner the relevant cross sections.

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