TAsP: Theoretical Astroparticle Physics

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Main scientific activities and achievements during the year 2020.

Axion Physics:

Explaining the origin of the Peccei-Quinn (PQ) symmetry that solves the strong CP problem is to date an open issue, as is also the mechanism that ensures that this symmetry is respected by effective operators up to a rather large dimension. In Ref. [1] we have shown how a certain type of gauge groups can automatically yield a perturbatively *exact* PQ symmetry and solve these problems. We have outlined a model in which the PQ symmetry is preserved at all operator dimensions, and we have also argued that this type of gauge groups can also enforce and protect accidental symmetries of the clockwork type. Finally we have presented a toy model where a 'clockwork' axion arises from a single breaking of the gauge and global symmetries.

In most models the axion couples to standard model fields with a strength proportional to its mass. In Ref. [2] we have put forth a type of constructions in which this theoretical constraint is evaded: the axion coupling to photons, nucleons or leptons can be enhanced selectively without increasing the axion mass.

In Ref. [3] we have shown that the interpretation in terms of solar axions of the excess of electron recoils reported by the XENON1T collaboration in June 2020, is not tenable when confronted with astrophysical observations of stellar evolution. We have discussed why the emission by the Sun of a flux of axions sufficiently intense to explain the anomalous data would radically alter the distribution of certain type of stars in the color-magnitude diagram, and would also clash with a certain number of other astrophysical observables. This paper has been highlighted as *Physics Review Letter Editors' Suggestion* "Due to its particular importance, innovation, and broad appeal".

Ref. [4] is a thorough review of the present status of the art in axion physics. This 120 pages long article represents an year-long effort, and after less than one year from its publication has already collected about one hundred citations.

The strongest upper bounds on the axion mass come from the SN1987A neutrino burst duration that depends on the axion couplings to nucleons, and from white-dwarf cooling rates and red-giant evolution, which involve the axion-electron coupling. We had previously argued that in DFSZ models with generation-dependent PQ charges, approximate axion-nucleon decoupling can occur, strongly relaxing the SN1987A bound. However, in general the axion remains in coupled to electrons, unless an ad hoc cancellation is engineered. In Ref.[5] we have shown that axion-electron decoupling can instead be implemented without extra tuning in models with three Higgs doublets.

Physics of the dark sectors:

Axion-like particles (ALPs) can provide a portal to new states of a dark sector. In Ref. [6] we have studied the phenomenology of this portal when the ALP mainly decays invisibly, while its interaction with the standard model sector proceeds essentially via its coupling to electrons and/or photons. We have re-analysed existing limits from various collider and beam dump experiments, including in particular ALP production via $e^{\pm}$ interactions in addition to the usual production through ALP-photon coupling. We have also illustrated the prospects for ALP searches at the positron fixed-target experiment PADME, and the future reach of an upgraded experimental setup.

Hadronic showers transfer a relevant amount of their energy to electromagnetic sub-showers. In

Ref. [7] we have shown that the generation of "secondary" dark photons in sub-showers is significant and typically dominates the production at low dark photon masses. The resulting dark photons are however substantially less energetic than the ones originating from mesons decay. We have illustrated this both semi-analytically and through Monte Carlo simulations. We have updated existing limits on vector-mediator scenarios for light dark matter by including the new production processes.

Neutrino Mass Models:

The flavour neutrino puzzle is often addressed by considering neutrino mass matrices with a certain number of vanishing entries ($m_{ij} = 0$ for some values of the indices), since a reduction in the number of free parameters increases the predictive power. Symmetries that can enforce textures zero can also enforce a more general type of conditions. In this case the neutrino mass matrix can have all entries non-vanishing with no reduction in its predictive power. In Ref. [8] we have classified all generation-dependent U(1) symmetries which, in the presence of two leptonic Higgs doublets, can reduce the number of independent high-energy parameters of the type-I see-saw to the minimum number compatible with non-vanishing neutrino mixings and CP violation. These symmetries are broken above the scale where the effective operator is generated and can thus remain covert, in the sense that no explicit evidence of the symmetry can be read off the neutrino mass matrix, and different symmetries can give rise to the same low-energy structure. We have found that only two cases are viable: one yields a structure with two zero-textures already considered in the literature, the other has no zero-textures and has never been considered before. It predicts normal ordering, a lightest neutrino mass $\sim 10\,\text{meV}$ and a Dirac phase $\delta \sim 3\pi/2$.

Publications

1 Exact accidental U(1) symmetries for the axion,
L. Darmé and E. Nardi, [arXiv:2102.05055 [hep-ph]].

2 Selective enhancement of the QCD axion couplings,
L. Darmé, L. Di Luzio, M. Giannotti and E. Nardi,
Published in: Phys. Rev. D **103**, no.1, 015034 (2021).

3 Solar axions cannot explain the XENON1T excess,
L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia and E. Nardi,
Published in: Phys. Rev. Lett. **125**, no.13, 131804 (2020).

4 The landscape of QCD axion models,
L. Di Luzio, M. Giannotti, E. Nardi and L. Visinelli,
Published in: Phys. Rept. **870**, 1-117 (2020).

5 Axion-electron decoupling in nucleophobic axion models,
Fredrik Björkeroth, Luca Di Luzio, Federico Mescia, Enrico Nardi et al.
Published in Phys.Rev. D101 (2020) no.3, 035027.

6 Invisible decays of axion-like particles: constraints and prospects,
L. Darmé, F. Giacchino, E. Nardi and M. Raggi, [arXiv:2012.07894 [hep-ph]].

7 New production channels for light dark matter in hadronic showers,
A. Celentano, L. Darmé, L. Marsicano and E. Nardi,
Published in: Phys. Rev. D **102**, no.7, 075026 (2020).

8 Covert symmetries in the neutrino mass matrix,
Fredrik Björkeroth, Luca Di Luzio, Federico Mescia, Enrico Nardi,
Published in JHEP 2002 (2020) 066.