

# Dark Energy and Dark Matter

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**Abstract.** We present the research carried out in México in the area of cosmology. In particular the contributions towards elucidating the nature and dynamics of dark energy and dark matter.

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## 1. INTRODUCTION

In the past few years different observations have lead to conclude that the universe is flat and filled with an energy density with negative pressure generically called Dark Energy "DE". This energy density gives at present time 73% of the energy density of our universe. Besides DE the universe contains Dark Matter "DM" required by matter clustering. Neither DE nor DM are contained in the well established standard model of particle physics "SM" which represents only (4 – 5)% of the energy density of our universe.

The physical process that gives rise to dark matter and dark energy is yet unclear. It is therefore very interesting that cosmology rises today some of the most relevant questions in particle physics, namely, what is the nature of dark energy and dark matter, i.e. of 95% of the energy density of our universe.

This paper is organized as follows. In section 2 we present the works done in trying to understand the dynamics of dark matter from a phenomenologically and numerical point of view. In section 2.2 a new proposal in determining the Hubble constant using gamma ray burst is described. In section 3 we present research carried out in parameterizing dark energy and dark matter as scalar fields. We give in section 3.1 a general analysis on the cosmological evolution of scalar fields as dark energy, in section 3.2 a model of dark energy and dark matter is derived from particle physics (gauge theory), while in section 3.3 explicit examples of dark energy and dark matter as scalar fields are presented. In section 4 works on scalar tensor theories applied to cosmology are considered. We present in section 4.1 a proposal to explain an apparent galactic periodicity, in section 4.2 we discuss galaxy formation and dynamics, and finally in section 4.3 models of dark matter in the Newtonian limit and models of dark energy with inhomogeneities are presented.

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## 2. DARK MATTER AND DARK ENERGY PHENOMENOLOGY

### 2.1. DARK MATTER

One of the goals of the UNAM astrophysics group was to connect the predictions of the current cosmological paradigm of cosmic structure formation, the so-called Cold Dark Matter (CDM) model, with the properties of present-day disk galaxies -the most abundant in the Universe. By modelling in detail the formation and evolution of disk galaxies inside hierarchically growing CDM halos, several properties and correlations of this population of galaxies were predicted (e.g., [1, 3], [13]). It was evidenced that the CDM model provides initial and boundary conditions to disk galaxy evolution, which allow to explain important observed properties and correlations of galaxies, for instance the nearly exponential mass surface density distribution and the nearly flat rotation curves of disk galaxies, as well as the observed tight luminosity-circular velocity correlation (Tully-Fisher relation) and its scatter. It was shown that even local properties, as the ones of the solar neighborhood in our Galaxy, can be well explained by the conditions provided by the CDM model [4].

An extensive work has been also done in the direction of predicting the properties of CDM halos as a function of their environment [2]. The results obtained in these works carried out with cosmological N-body simulations, suggest that the CDM model could also be at the basis of the well known dependence of galaxy properties on environment.

The UNAM astrophysics group has also explored the consequences of modifying the CDM model at small scales, where apparently some potential difficulties arise. They were among the first groups in proposing weak self-interacting CDM particles in order to reduce the high inner mass concentration predicted for the CDM halos [9, 10]. First empirically, and then by means of high-resolution cosmological N-body simulations [7], they concluded that the cross-section per unit of dark particle mass should be inversely proportional to the interaction velocity.

Other alternative studied by this group was Warm Dark Matter (WDM). By means of high-resolution N body simulation, they found that the amount of substructure (sub-halos) inside Milky-Way-size halos decrease from a very high number, when CDM is used, to a low number, comparable with the observed abundance of satellites galaxies, when WDM, with particle masses of 1-2 KeV, is used [6]. The inner structure of the halos remains roughly the same in both cases, though the halos are less concentrated for WDM particles [4]. These works prompted the intensive research of WDM particles, like sterile neutralinos, from the point of view of particle physics.

### 2.2. DARK ENERGY

The UNAM astrophysics group, in collaboration with INAF-OAB (Italy) researchers, has introduced a new kind of standard candle able to extend the Hubble diagram to redshifts much higher than those of type Ia supernovae. With this new cosmological probe, tight constraints to the dark energy (DE) parameters can be obtained, because some model degeneracies are broken due to the high redshift range. The new standard

candles are the Gamma Ray-Bursts (GRBs) with measured redshift, which obey tight correlations among their energetics and some observable properties. The group has developed a Bayesian approach to calibrate these correlations and at the same time to constrain cosmological parameters using the Hubble diagram [11]. Besides, a new improved correlation has been discovered by Firmani et al. [12]. First cosmological constraints based on this correlation were reported for GRBs alone [13] and for the combination of GRBs and SNIa [14]. The results are in excellent agreement with the  $\Lambda$ CDM concordance cosmological model (minimal case), i.e. the cosmological constant as DE. Models that imply an evolving equation-of-state parameter for the DE are not favored.

### 3. SCALAR FIELDS IN COSMOLOGY

#### 3.1. General Analysis of Scalar Fields

At the Instituto de Física (UNAM), there has been considerable effort to work on problems in the interface between particle physics and cosmology [17]-[31]. In particular on the nature of dark energy. Perhaps, DE is best described in terms of scalar fields. The evolution of scalar fields has been widely studied and some general approaches can be found in [17]. It is shown that a scalar field with potential  $V$  only leads to a late time acceleration (i.e. dark energy) only if  $V'/V \rightarrow const < \sqrt{3}$  or  $V'/V \rightarrow 0$  with a non oscillating behavior [17].

#### 3.2. Dark Group: Dark Energy and Dark Matter

Applications of scalar fields in cosmology derived from gauge field theory can be found in [17]-[31]. A very interesting model of dark energy and dark matter derived from particle physics (field and gauge theory) was proposed in [20, 22, 26, 31]. The starting point of this model is a dark gauge group "DG" whose particles interact with the standard model "SM" only via gravity. The dark energy model is a  $SU(N_c = 3)$  gauge group with  $N_f = 6$  elementary particles in the fundamental representation and with only gravitational interaction with the standard model of particle physics. Besides the choice of  $N_c = 3$  and  $N_f = 6$  there are no other free parameters (notice that it is at the same footing as the SM since there is no explanation in the SM of the choice of gauge groups nor why there are three families).

At high energies the dark elementary fields are massless and the energy density redshifts as  $\rho_{DG} \propto a^{-4}$ . The ratio  $\rho_{DG}/\rho_r$  is therefore constant and it is given only in terms of the number of particles. The gauge coupling constant becomes strong at lower energies, i.e. the gauge group is asymptotically free (as the strong force given by QCD). At low energies a phase transition takes place due to a strong gauge coupling constant. At this scale the dark elementary fields are bound together producing gauge invariant states. The relevant scale for this process is the condensation scale  $\Lambda_c$  and for a gauge group  $SU(N_c)$  with  $N_f$  matter fields it is given by the one-loop renormalization group

equation [20]  $\Lambda_c = \Lambda_{gut} e^{-8\pi^2/b_0 g_{gut}^2}$  where  $b_0 = 3N_c - N_f$  is the one-loop beta function and  $\Lambda_{gut} \simeq 10^{16} \text{GeV}$ ,  $g_{gut}^2 \simeq 4\pi/25.7$  are the unification energy scale and coupling constant, respectively. Motivated by grand unification theories and by string theory we have constrained the dark gauge group and  $\Lambda_{DE}$  to be unified with the standard model gauge groups at the unification scale. Our dark energy model has  $N_c = 3, N_f = 6$  giving  $b_0 = 3$  and  $\Lambda_c = 42 \text{eV}$ . Strong gauge interactions produce a non-perturbative scalar potential  $V$  below  $\Lambda_{DE}$ . This potential can be calculated using Affleck-Dine-Seiberg potential. The superpotential for a non-abelian  $SU(N_c)$  gauge group with  $N_f$  massless fields can be calculated and the resulting scalar potential in SUSY for one dynamical meson field  $\phi^2 \equiv \langle Q\bar{Q} \rangle$  ( $Q$  are the fundamental fields of the original gauge group) which represents a pseudo-Goldstone boson, is  $V = \Lambda_c^{4+n} \phi^{-n}$  with the exponent of  $\phi$  given by  $n = 2[1 + 2/(N_c - N_f)] = 2/3$  [20, 22, 31].

In order to study the cosmological evolution of  $\phi$  with potential  $V$  in a Friedman-Robertson-Walker metric the initial value on  $\phi$  must be chosen. Since the elementary fields are bounded at the condensation scale  $\Lambda_{DE}$ , when the gauge coupling constant becomes strong, it is this scale the relevant physical scale and we therefore take  $\phi_i = \Lambda_c$ . With this choice the initial mass of  $\phi$  is  $m^2 = \partial^2 V / \partial \phi^2 \simeq \Lambda_{DE}^2$  which sets the correct mass scale for the process. Notice that in QCD the mass of the pion and proton is of the same order of magnitude as the QCD scale  $\Lambda_{QCD} \simeq 200 \text{MeV}$ . Global symmetries and SUSY protect the mass of the quintessence field  $\phi$ . In fact the ADS superpotential is exact and receives no corrections. The energy density  $\rho_{DG}$  tracks radiation for a long period of time, including nucleosynthesis "NS" epoch, since all the particles are massless. The onset of the quintessence field is at a very late time ( $a_c \simeq 10^{-6}$ ) and close to matter-radiation equality ( $a_{eq} \simeq 10^{-4}$ ). The fact that  $\Lambda_{DE}$  is so small and the appearance of the quintessence field is at such a late time solves the coincidence problem since it implies that an accelerating universe will necessarily be at a scale factor larger than  $a_c$  and  $a_{eq}$ , i.e. close to present time.

If we have  $N_c < N_f$  then on top of the gauge singlet meson fields we can have gauge singlet dark baryons  $B^{i, \dots, N_c} = \prod_i^{N_c} Q^i$  and anti baryons. These particles get a non-vanishing mass due to non-perturbative effects (like protons and neutrons in QCD). These baryons could give the dark matter of the universe [26]. The order of magnitude of the mass of the DM particle can be estimated by the condensation  $m = c \Lambda_{DE}$  with  $c = O(1 - 10)$  a constant (in the case of QCD  $m_{proton}/\Lambda_{QCD} = 4.5$ ). From cosmology it is known that  $\Omega_{DM0} = 0.25 \pm 0.05$ . From entropy conservation  $\Omega_{DM}$  can be determined giving  $\Omega_{DM0} = 0.25(0.74/h_0)^2 (m/g_{dec} \text{eV})$  [26]. So a dark matter mass of  $m \simeq g_{dec} \text{eV}$  is of the same order of magnitude ( $g_{dec} = 106, 228$  for the SM and SUSY-SM, respectively) as the mass given by gauge theory dynamics  $m = c \Lambda_{DE} = c 42 \text{eV}$ . Comparing the model with the data (SN1a Golden set and WMAP1) it has an excellent fit and equivalent to  $\Lambda_{CDM}$  giving a  $\chi^2/d.o.f. = 1.08$  [31].

### 3.3. Scalar Fields, Dark Energy and Dark Matter

There is a group at Centro de Investigación y de Estudios Avanzados del IPN, in México, which is working in problems of dark matter and dark energy. This group has

produced research in dark matter and dark energy since 1999. They have worked on different research lines, specially on the nature of the cosmological and galactic dark matter and on the nature of dark energy. The first work was a proposition about the nature of the dark matter in galaxies [32]. In this work they argue that all unification theories, from the standard model of physics to the superstrings theory, need to postulate scalar fields somehow, in order to have certain consistency. Therefore they propose to investigate the hypothesis that the dark matter is of scalar field nature, calling it the Scalar Field Dark Matter (SFDM) model. In [32] they show that using a scalar field with an exponential potential, the rotation curves of galaxies can be fitted well. In a further paper [33] they investigate the hypothesis that not only the dark matter, but also the dark energy are provided by the same scalar field. They came to the conclusion that this is not possible; later it was shown that a complex scalar field as dark matter in cosmos is also ruled out [35]. Therefore, in [34] they investigate a model with two scalar fields, the first one contains a cosh potential, it is interpreted as the dark matter, and the second one contains a sinh potential and it is interpreted as the dark energy, a quintessence field. This last hypothesis, consisting in studying a quintessence field with a sinh potential, was introduced first by Luis Ureña and Tonatiuh Matos in [36]. This potential is one of the most popular potentials for quintessence in the literature. The study of the perturbations and the structure formation in the linear regime of the two scalar fields model was investigated in [37]. They conclude that the  $\Lambda$  Cold Dark Matter ( $\Lambda$ CDM) model and the SFDM model give exactly the same predictions for the structure formation of the universe at cosmological level. They concluded that if there is a difference between the  $\Lambda$ CDM model and the SFDM model it must be at galactic level. One interesting feature of this model, is that the free constants of the model, all of them, were fixed using cosmological observations. In [38] the group of researchers was extended to UNAM, and together they investigated the behavior of the collapse of a scalar field, in order to understand it in the non-linear regime of fluctuations. The result was a big surprise, they found that using the values of the fixed free parameters of this model, the scalar field will collapse with a critical mass  $M \sim 10^{12}M_{\odot}$ , which implies that this model could be able to explain the structure formation in cosmos and also the galaxy formation. In 1990's it was proved that the cosh potential is a renormalizable potential, with a renormalization scale  $\Lambda \sim 2M_{Planck}$ . This fact gives the possibility that the scalar field has a fundamental origin or that the scalar field goes beyond the Planck era. In [40] two members of the group have summarized the results and the main ideas about the hypothesis of the SFDM model at cosmological level.

Other branch of research of this group is the study of the dark matter in galaxies. In [41], they studied the general conditions of a metric in general relativity, in order to reproduce the rotation curves of galaxies. They gave a general metric in terms of the rotations velocity, using the geodesics of the metric. This study was applied to many systems and proposals of dark matter in [42]. One of the fields which was able to reproduce the behavior of the galaxies was just the scalar field, as proposed in [32]. In [44] it was proposed that the scalar field could have other kind of scalar field potentials. So, in [45] general statements and conditions for the formation of a scalar field halo were established. Some galaxies were fitted using this hypothesis (see [43]); it was then clear that for big galaxies, it was possible to explain their rotation curves, starting with the hypothesis of a scalar field as dark matter in galaxies. Using n-body simulations

it was also possible to reproduce the baryonic part of a galaxy formation, using as a background the gravitational potential of a scalar field [46]. The question about the nature of this scalar field is still open, nevertheless, in [47] the hypothesis that the dark matter and the quintessence fields could be the same field was investigated and discarded in [48]. Within this hypothesis, the first investigations on the collapse of the scalar field as dark matter in galaxies were done in [38], and a further investigation on the cooling conditions [49] and stability [50], have shown that scalar fields collapse very early in the universe and are very stable. The authors have shown in these papers that the scalar field virialize very fast and remains oscillating for a very long time. This is the reason of the name of these objects, they are called oscillatons. These oscillatons have very interesting features, but the most important one is that they have a flat density profile, resembling the real halo of a galaxy. In [51], they show, using some approximations, that the central density profile of an oscillaton is flat. This fact is confirmed in [52], using many quantum states of the Bose-Einstein Condensate. This feature is maybe one the most important ones of the SFDM hypothesis. Observations show that dwarf galaxies have a flat density profile, and the traditional  $\Lambda$ CDM paradigm contains a cusp density profile, in contradictions with observations. Here, the SFDM model show an advantage over the  $\Lambda$ CDM paradigm. Other advantage of the SFDM model over the  $\Lambda$ CDM paradigm is that the SFDM model contains a natural cut of the mass power spectrum, causing a suppression of the formation of small galaxies. This prediction of the SFDM model is confirmed by observations in satellite galaxies. Observations show that there are very few satellite galaxies around the Milky way, in contradiction with the  $\Lambda$ CDM paradigm, which predicts more than 10 times in excess [37]. Other interesting feature of the SFDM model is that in the presence of a supermassive black hole, these oscillatons are swallow by the black hole as expected, but in [53] the authors show that the rate of scalar field matter that is swallowed by the black hole is of order of a planet per year. Too small to be significant. That means that scalar field can live together with a supermassive black hole in the galaxy.

Other line of research of the groups in Cinvestav and UNAM is the study of general properties of the halos of galaxies, using a more powerful tool, i.e., general relativity. Using the fact that the Navarro-Frenck-White (NFW) is the profile derived from n-body simulations for the halo of a galaxy, this group gives a general relativistic analysis of this profile. First they found the space-time metric arising from this profile [54]. They argue that we do not know the nature of the dark matter, thus it is necessary to use the best tool for analyzing the gravitational fields. Second, they study the thermodynamic of this space-time [55] and obtain some conclusions about the thermodynamical nature of dark matter, if the density profile is of the NFW (see also [56]). It is also possible to carry out the thermodynamical analysis of the halo of a galaxy [57] (see also [58]), without supposing any special profile. With this analysis it is possible to constrain the mass of the dark matter particles. These criteria are able to give some constrains on the central temperature of the halo. There are some other alternative candidates studied by the Mexican groups. Some examples are stellar mini-Machos [59], which consists in small scalar field stars which behave like dark stars. This hypothesis do not violate the Big Bang Nucleosyntheses constrains, because the minimachos are not baryonic. So, the minimachos can be stars around the galaxy. Nevertheless, microlensing Macho observations constrain a lot this hypothesis. Other hypothesis under research by the

Mexican groups is a thermodynamic study of galaxies, but using the alternative entropy introduced by Tsallis [60],[61], [62], where the non-local character of it enables to fit the rotation curves of galaxies. A further alternative is a non-linear theory of relativity: in [63] the authors show that with this theory it is possible to recover the results of SFDM in some cases. A review on Structure Formation in spanish can be found in [64].

In the context of the Dark Energy, the group at Cinvestav proposed a model of quintessence using a sinh scalar field potential. This is convenient because the sinh behaves as power law potential for large scalar field values and this permits to fit well the Big Bang Nucleosynthesis constrains. On the other hand, for small scalar field values, the sinh potential is an exponential and this behavior permits to fit very well the SNIa constrains. This potential has received a good acceptance in the cosmology community. There is also the study of the dynamics of a scalar field with a negative kinetic term, the so called phantom field [65].

Other line of research is the hypothesis that the inflaton is at the same time the dark matter or the dark energy or both. This is possible in the context of Brane cosmology. Using an exponential potential in the Brane cosmology paradigm, in [66] the authors show that an inflaton field can remain as dark matter after inflation. One problem they have to face is that the scalar field can not reheat the universe, as in the traditional inflation paradigm. Therefore they reheat the universe supposing that a fraction of  $10^{-16}$  of the scalar field energy density becomes primordial black holes. These black holes can evaporate by Hawking radiation producing a huge ammount of heat, enough to reheat the universe. The primordial black holes burn before BBN. Other interesting feature is that the branes provoke a quadratic term of the density in the Friedmann equation. This term dominates the evolution and inflates the universe. After inflation the density becomes very small and the linear term in the Friedmann equation dominates. If one starts with a normal non-inflationary potential, this causes a natural gracefull exit, an exit of the inflationary epoch, when the universe passes from the quadratic to the linear behavior of the density. The value for the free constants used in this model are the ones used in the SFDM model, in such a way that the SFDM can inflate the universe in the presence of branes. In [67], solutions for different potentials in this paradigm were found, in all of them the gracefull exit was confirmed. This show that the inflaton in the brane paradigm can exit from inflation easily and can become dark matter in an easy way. In [68], another way to obtain reheating was studied in the framework of brane cosmology. A further investigation starts from string theory. Using the Landscape string theory and a quadratic potential plus a constant, in [69] it was shown that this potential can produce the inflaton together with the dark matter and that the constant can be the cosmological constant. Thus, with this potential in the Landscape theory it is possible to have it all: inflation, dark matter and dark energy. In the same way, starting with the IIB superstring theory, compactifying on an orbifold with 32 fluxes, the dilaton acquires an effective potential, which has a cosh term and a cosmological constant. With this model, in [70] (see also [71]) the authors recover the  $\Lambda$ CDM model, but because of the presence of the branes, the dilaton inflates the universe as well. This is the first time that a string theory makes contact with reality, the first time that this theory has a phenomenology. The result is that there are some differences between string theory and the  $\Lambda$ CDM model. The epoch of recombination is very different in both models, in the  $\Lambda$ CDM model the density rates evolve very smoothly, while in the string theory models they oscillate.

Other difference is that the density profile of galaxies is cusp in the  $\Lambda$ CDM model and flat, as observed, in the string theory models. This differences can be used to ruled out one of these models.

Some reviews of the SFDM model can be found in [72], [73], [74], [75], [76], [77] and [78], in different contexts. Some reviews for no-specialists (in spanish) can be found in [79] and [80].

## 4. COSMOLOGY WITH SCALAR-TENSOR MODELS

### 4.1. Galactic Periodicity

In the work of [81]-[86] they propose a scalar-tensor system, by including a scalar field non minimal coupled to the curvature. In this model the resulting gravitational constant varies with time and allows for a possible explanation the apparent galactic periodicity of 128Mpc detected at the early 1990. This model is compatible with the bound on primordial nucleosynthesis as well as with solar system bounds on time variation of coupling constants. Furthermore, the model allows for an accelerating universe at late times without the need to introduce a cosmological constant.

### 4.2. Galaxy formation and dynamics

Within the context of galaxy formation and galaxy dynamics several works have been presented [87]-[91] and make use of scalar tensor theories. These works can allow for a better understanding of the nature and dynamics of dark matter.

In [87], simulations within the framework of scalar-tensor theories, in the Newtonian limit, to investigate the influence of massive scalar fields on the dynamics of the collision of two equal spherical clouds are presented. They employ a SPH code modified to include the scalar field to simulate two initially non-rotating protogalaxies that approach each other, and as a result of the tidal interaction, an intrinsic angular momentum is generated. They have obtained sufficient large values of  $J/M$  to suggest that intrinsic angular momentum can be the result of tidal interactions. In [88], a family of potential density pairs has been found for spherical halos and bulges of galaxies within the Newtonian limit of scalar tensor theories of gravity. The scalar field is described by a Klein Gordon equation with a source, that is coupled to the standard Poisson equation of Newtonian gravity. The net gravitational force is given by two contributions: the standard Newtonian potential plus a term stemming from massive scalar fields. General solutions have been found for spherical systems. In particular, the authors compute potential-density pairs of spherical, galactic systems, and some other astrophysical quantities that are relevant to generate initial conditions for spherical galaxy simulations. In [89], they present a formulation for potential-density pairs to describe axi-symmetric galaxies in the Newtonian limit of scalar-tensor theories of gravity. The scalar field is described by a modified Helmholtz equation with a source that is coupled to the standard Poisson equation of Newtonian gravity. The net gravitational force is given by two contributions: the standard Newtonian potential plus a term stemming from

massive scalar fields. General solutions have been found for axisymmetric systems and the multipole expansion of the Yukawa potential is given. In particular, the authors have computed potential density pairs of galactic disks for an exponential profile and their rotation curves. In [90], they study the dynamics of spherical galaxies with the Navarro-Frenk-White (NFW) density profile within the Newtonian limit of scalar-tensor theories of gravity. The scalar field is described by a modified Helmholtz equation with a source and it is coupled to the Poisson equation of standard Newtonian gravity. The net gravitational force is given by two contributions: one coming from the standard Newtonian potential and other coming from the massive scalar fields. The authors found general solutions for spherical systems, and in particular, they obtain results for the potential density pairs and other relevant quantities of galactic spherical systems with the NFW density profile. Finally, in [91], the joint influence of numerical parameters such as the number of particles  $N$ , the gravitational softening length  $\dot{a}$  and the time-step  $t$  is investigated in the context of galaxy simulations. For isolated galaxy models the authors have performed a convergence study and estimated the numerical parameters ranges for which the relaxed models do not deviate significantly from its initial configuration. By fixing  $N$ , they calculate the range of the mean interparticle separation  $\bar{e}(r)$  along the disc radius. Uniformly spaced values of  $\bar{e}$  are used as  $\dot{a}$  in numerical tests of disc heating. They have found that in the simulations with  $N = 1\ 310\ 720$  particles  $\bar{e}$  varies by a factor of 6, and the corresponding final Toomre's parameters  $Q$  change by only about 5 per cent. By decreasing  $N$ , the  $\bar{e}$  and  $Q$  ranges broaden. Large  $\dot{a}$  and small  $N$  cause an earlier bar formation. In addition, the numerical experiments indicate, that for a given set of parameters the disc heating is smaller with the Plummer softening than with the spline softening. For galaxy collision models we have studied the influence of the selected numerical parameters on the formation of tidally triggered bars in galactic discs and their properties, such as their dimensions, shape, amplitude and rotational velocity. Numerical simulations indicate that the properties of the formed bars strongly depend upon the selection of  $N$  and  $\dot{a}$ . Large values of the gravitational softening parameter and a small number of particles results in the rapid formation of a well defined, slowly rotating bar. On the other hand, small values of  $\dot{a}$  produce a small, rapidly rotating disc with tightly wound spiral arms, and subsequently a weak bar emerges. The authors have found that by increasing  $N$ , the bar properties converge and the effect of the softening parameter diminishes. Finally, in some cases short spiral arms are observed at the ends of the bar that change periodically from trailing to leading and vice-versa the wiggle.

### 4.3. Newtonian Limit and Inhomogeneities

At the Instituto de Ciencias Nucleares, UNAM, research on dark matter has also been carried out [92]-[101]. In particular the studies on galactic dark matter can be placed in the context of incorporating models of galactic CDM halos in the framework of the Newtonian limit of General Relativity, as opposed to a purely Newtonian construction. They have studied the effects of the cosmological constant in the hydrostatic equilibrium of a CDM gas and they have also proposed a Relativistic Kinetic Theory approach to a collisionless CDM gas in which the particles are subjected to a generalized vector force

interaction (as opposed to be free falling). In either case, the Newtonian limit obtained from the strict general relativistic approach yields small (but significant) differences with a purely Newtonian framework. In other work they propose a CDM model in which the "particles" are not the usual supersymmetric neutralinos but asteroid sized "mini-MACHO's" formed by condensations of primordial scalar fields (larger MACHO's would have been detected by lensing). Current N-body numerical simulations cannot distinguish this change of granularity of CDM.

On the issue of dark energy, they have studied simple semi-analytical models of self-gravitating dark matter and dark energy in inhomogeneous conditions. These models allow for minimal and non-minimal coupling between DM and DE. The non-minimal coupling can be understood within the framework of scalar-tensor theories. These models illustrate how cosmological observational parameters, associated with a cosmic scale ( $> 300$  Mpc), are affected by inhomogeneity and anisotropy in scales smaller than the homogeneity scale [92]-[101].

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