Self-gravitating Systems of Dark Matter Particles

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1 Topics

The problem of the distribution of stars in globular clusters, and more general in galactic systems, has implied one of the results of most profound interest in classical astronomy. The pioneering works of Michie (1963) and King (1966) considered the effects of collisional relaxation and tidal cutoff by studying solutions of the Fokker-Planck equation. There, it was shown that stationary solutions are well described by pseudo-isothermal sphere models, based on simple Maxwell energy distribution functions with a constant subtracting term interpreted as an energy cutoff. An extension of this statistical analysis with thermodynamic considerations, which includes the effects of violent (collisionless) relaxation, was studied by Lynden-Bell (1967) with important implications to the problem of virialization of dark matter (DM) halos which are still of current interest.

Later on, in a series of works by R. Ruffini and collaborators (see, e.g., Ruffini and Stella, 1983 in Newtonian gravity and Gao et al., 1990 in GR), the emphasis changed from self-gravitating systems of classic stars (which verify Maxwellian distributions) to systems of fermionic particles, with the aim of describing galactic DM halos. In this line, an important contribution was given by Chavanis (2004), who studied generalized kinetic theories accounting for collisionless relaxation processes, obtaining a class of generalized Fokker-Planck equation for fermions with applications to DM halo formation. It was there explicitly shown the possibility to obtain, out of general thermodynamic principles, a generalized Fermi-Dirac distribution function including an energy cutoff, extending the former results by Michie and King to quantum particles.

Within this field of research, our group aims to contribute to the understanding of the DM nature. In particular, we mainly focus on a possible fermionic nature of the DM particles, and its consequences in astrophysics and cosmology.

2 Participants

2.1 ICRANet

- Faculty
  - C. L. Bianco (ICRANet, Italy)
  - J. A. Rueda (ICRANet, Italy)
  - R. Moradi (ICRANet, Italy)
  - R. Ruffini (ICRANet, Italy)
  - N. Sahakyan (ICRANet, Armenia)
  - G. Vereschagin (ICRANet, Italy)
  - S.-S. Xue (ICRANet, Italy)
  - Y. Wang (ICRANet, Italy)
- Adjunct Professors of the Facutly

  Carlos R. Argüelles (Universidad Nacional de La Plata & CONICET, Argentina)
- Researchers

  A. Krut (ICRANet, Pescara, Italy)

2.2 External on going collaborations

- K. Boshkayev (Al-Farabi Kazakh National University, Kazakhstan)
- M. I. Díaz (Universidad Nacional de La Plata, Argentina; Laboratoire de Physique, École Normale Supérieure, CNRS, Université PSL, Sorbonne Université, Université de Paris, France)

- F. D. Lora-Clavijo (Universidad Industrial de Santander, Colombia)
- D. L. Nacir (Universidad de Buenos Aires & CONICET, Argentina)
- N. Mavromatos (King's College London, U.K.; CERN, Switzerland)
- A. Moliné (Universidad Autónoma de Madrid, Spain; Universidade de Lisboa, Portugal)
- P. Rosati (University of Ferrara, Italy)
- C. Scóccola (Universidad Nacional de La Plata & CONICET, Argentina)
- M. F. Mestre (Universidad Nacional de La Plata & CONICET, Argentina)

2.3 Graduate Students

- E. A. Becerra (ICRANet; Sapienza University of Rome, Italy; Universidad Industrial de Santander, Colombia)
- M. Carinci (Sapienza University of Rome, Italy)
- G. Nurbakyt (ICRANet; Al-Farabi Kazakh National University, Kazakhstan)
- Rafael Ignacio Yunis (ICRANet, Sapienza University of Rome, Italy)
- G. Zhumakhanova (ICRANet; Al-Farabi Kazakh National University, Kazakhstan)

3 Highlighted Publications 2021

3.1 Fermionic dark matter and galactic structures

The extensive and continuous monitoring of the closest stars to the Galactic center has been producing over decades a large amount of high-quality data of their positions and velocities. The explanation of these data, especially the S2 star motion, reveals the presence of a compact source, Sagittarius A* (Sgr A*), whose mass must be about $4 \times 10^6\ M_\odot$. This result has been protagonist of the awarded Nobel Prize in Physics 2020 to Reinhard Genzel and Andrea Ghez "*for the discovery of a supermassive compact object at the centre of our galaxy*". Traditionally, the nature of Sgr A* has been attributed to a supermassive black hole (SMBH), even though a proof of its existence is absent. Further, recent data on the motion of the G2 cloud show that its post-peripassage velocity is lower than the expected one from a Keplerian orbit around the hypothesized SMBH. An attempt to overcome this difficulty has used a friction force, produced (arguably) by an accretion flow whose presence is also observationally unconfirmed.

We have advanced in Argüelles et al. (2018) and in Becerra-Vergara et al. (2020, 2021); Argüelles et al. (2021a) an alternative scenario that identifies the nature of the supermassive compact object in the Milky Way center, with a highly concentrated core of DM made of fermions (referred from now on as *darkinos*). The existence of a high dense core of DM at the center of galaxies had been demonstrated in Ruffini et al. (2015), where it was shown that *core-halo* profiles are obtained from the Ruffini-Argüelles-Rueda (RAR) fermionic DM model. In the RAR model, the DM galactic structure is calculated treating the *darkinos* as a self-gravitating system at finite temperatures, in thermodynamic equilibrium, in general relativity. It has been already shown that this model, for *darkinos* of 48–345 keV, successfully explains the observed halo rotation curves of the Milky Way (Argüelles et al., 2018) as well as the ones of other galaxy types (Argüelles et al., 2019).

Therefore, in the year 2020, and more recently in 2021, we move forward by performing first in Becerra-Vergara et al. (2020) and then in Becerra-Vergara et al. (2021); Argüelles et al. (2021a), observational tests of the theoretically predicted dense quantum core at the Galactic center within the DM-RAR model. Namely, to test whether the quantum core of *darkinos* could work as an alternative to the SMBH scenario for SgrA*. For this task, we have first shown in Becerra-Vergara et al. (2020) that the sole DM core, for 56 keV *darkinos*, explains the orbit of S2 (position and radial velocities) and G2 with even better accuracy than the traditional Scwarzchild BH scenario, and without the need to invoque a drag force nor other external agents acting on G2. More recently in Becerra-Vergara et al. (2021), we have extended the above results to all the best observationally resolved S-cluster stars, namely to the up-to-date astrometry data of the 17 S-stars orbiting Sgr A*, achieving to explain the dynamics of the S-stars with similar (and some cases better) accuracy compared to a central BH model (see Fig. 3.1), strengthen the alternative DM nature of Sgr A*.

An important complementary result to the above two, was recently published in Argüelles et al. (2021a), aimed this time to the study of the periapsis precession of the S2 star orbit. We have there quantified for the first time within the RAR-DM model, the effects on the S2-star periapsis (precession) shift due to an extended DM mass filling the S2 orbit, in contrast with the vacuum solution of the traditional Schwarzschild BH scenario. The main result can be summarized as follows: while the Schwarzschild BH scenario predicts a unique prograde precession for S2, in the DM scenario it can be either retrograde or prograde, depending on the amount of DM mass enclosed within the S2 orbit, which in turn is a function of the *darkino* mass. We further show in Fig. 3.2 the relativistic precession of S2 projected orbit, in a *right ascension - declination* plot. It can be there seen that while the positions in the plane of the sky nearly coincide about the last pericentre passage in the three models, they can be differentiated close to next apocentre. Specifically, the upper right panel evidences the difference at apocentre between the prograde case (as for the BH and RAR model with $m = 58$ keV), and the retrograde case (i.e. RAR model with $m = 56$ keV).

Unfortunately, as can be already evidenced from Fig. 3.2, all the current and publicly available data of S2 can not discriminate between the two models, but upcoming S2 astrometry close to next apocentre passage could potentially establish if Sgr A* is governed by a classical BH or by a quantum DM system.

A further very interesting consequence of this scenario is that, a core made of these *darkinos*, becomes unstable against gravitational collapse into a BH

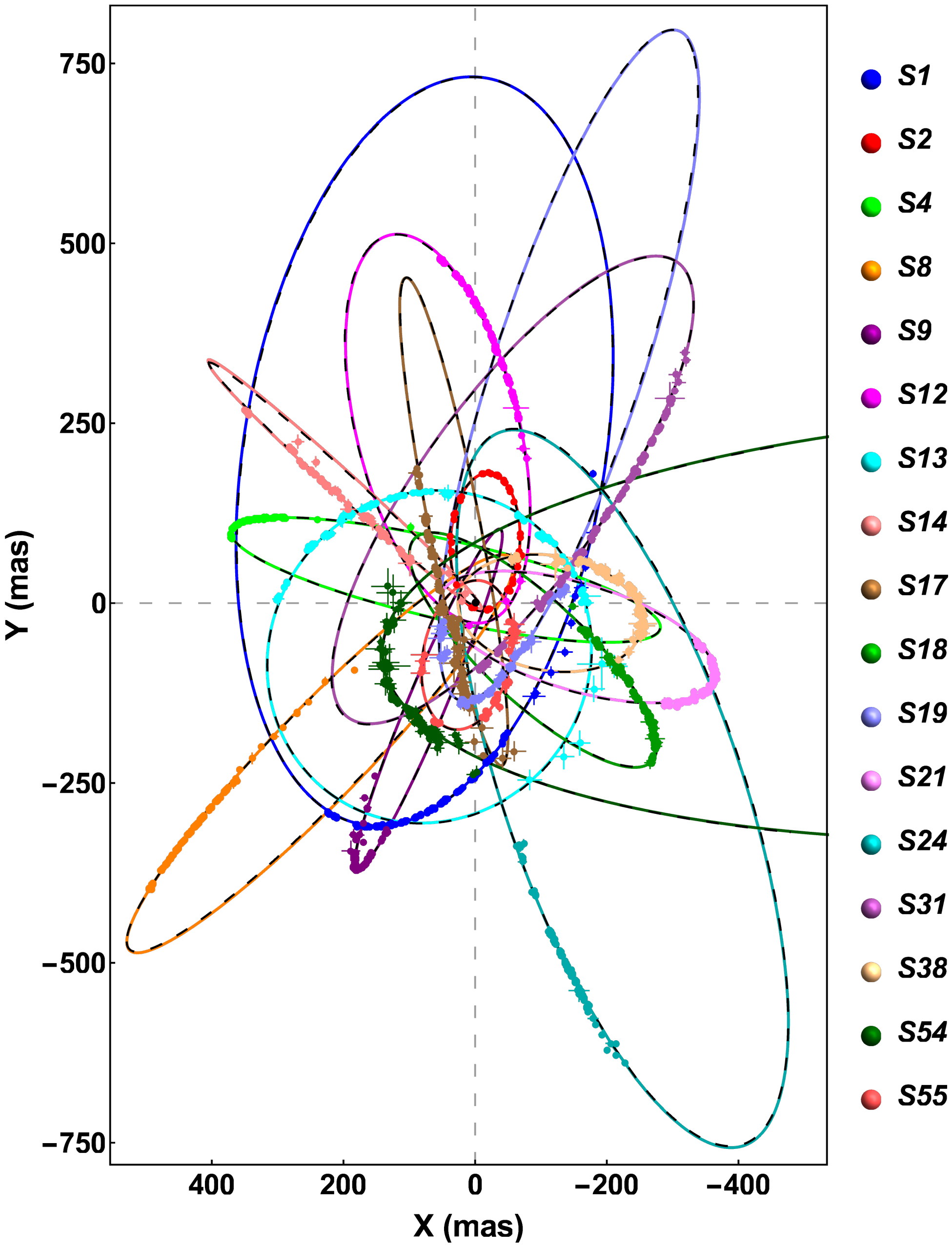

Figure 3.1: Best-fit orbits for the 17 best-resolved S-star orbiting Sgr A*. It shows the projected orbit on the sky, X vs. Y, where X is right ascension and Y is declination. The *black dashed curves* correspond to the BH model and the *colored curves* to the RAR model for $m \approx 56$ keV fermions. The astrometric data was taken from Refs. Do et al. (2019); Gillessen et al. (2009, 2017). Figure taken from Ref. Becerra-Vergara et al. (2021)

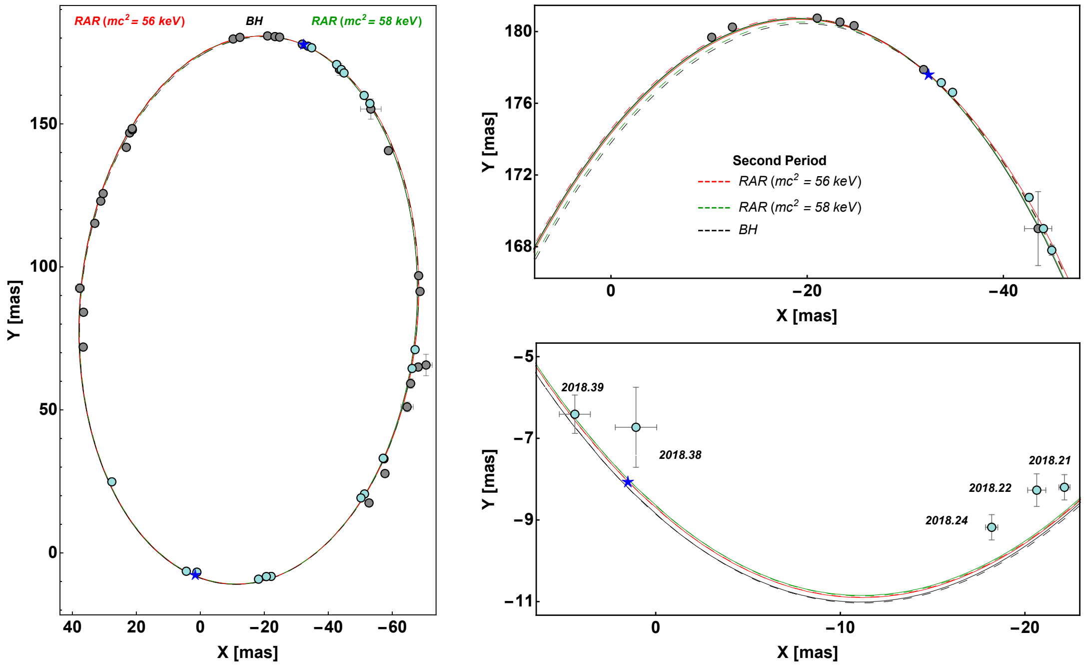

Figure 3.2: Relativistic precession of S2 in the projected orbit on the plane of the sky as predicted in the BH and RAR DM models. While it is prograde for the BH and RAR (m = 58 keV) (in dashed black and green respectively), it is retrograde for the RAR DM model (m = 56 keV) (in dashed red). The solid (theoretical) curves and gray (data) points correspond to the first period (≈ 1994–2010) while the dashed (theoretical) curves and cyan (data) points to the second period (≈ 2010–2026). *Right panels*: zoom of the region around apocentre *(top panel)* and pericentre *(bottom panel)*. The astrometric measurements are taken from Do et al. (2019)

for a threshold mass of $\sim 10^8\ M_\odot$. That is, collapsing DM cores can provide the BH seeds for the formation of SMBHs in active galaxies (such as M87), without the need of prior star formation, or other BH seed mechanisms involving super-Eddington accretion rates. This topic is also of major interest and was studied in detail by part of our group this year in another pubblication (see section below).

The two works summarized in this section together with the one introduced in the above paragraph and explained further in next section, have been one of the most important results of ICRANet in 2021. The fact that the center of our Galaxy could harbor a concentration of DM instead of a massive BH, and that the core-collapse of DM halos can offer a novel mechanism of SMBH formation, have attracted worldwide attention. Different Press Releases as well as more than hundred of different scientific news and blogs were published and released this year, see e.g:

- https://phys.org/news/2021-06-black-hole-center-milky-mass.html
- https://www.sciencealert.com/wild-new-paper-proposes-the-center-of-the-milky-way-might-not-be-a-black-hole?
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3.2 Formation and stability of fermionic dark matter halos in a cosmological framework

The formation and stability of collisionless self-gravitating systems are long standing problems, which dates back to the work of D. Lynden-Bell in 1967 on violent relaxation, and extends to the issue of virialization of DM halos. An important prediction of such a relaxation process is that spherical equilibrium states can be described by a Fermi-Dirac phase-space distribution, when the extremization of a coarse-grained entropy is reached. In the case of DM fermions, the most general solution develops a degenerate compact core surrounded by a diluted halo. As we have recently shown in Argüelles et al. (2018, 2019); Becerra-Vergara et al. (2020), the *core-halo* profiles obtained within the fermionic DM-RAR model explain the galaxy rotation curves, and the DM core can mimic the effects of a central BH. A yet open problem is whether this kind of astrophysical *core-halo* configurations can form at all in nature, and if they remain stable within cosmological timescales. We have assessed these issues in a very recent article (Argüelles et al., 2021b).

Specifically, we have there performed a thermodynamic stability analysis in the microcanonical ensemble for solutions with given particle number at halo virialization in a cosmological framework. For the first time, we demonstrate that the above *core-halo* DM profiles are stable (i.e. maxima of entropy) and extremely long lived. We find the existence of a critical point at the onset of instability of the *core-halo* solutions, where the fermion-core collapses towards a supermassive black hole. For particle masses in the keV range, the core-collapse can only occur for $M_{\rm vir} \gtrsim 10^9 M_\odot$ starting at $z_{\rm vir} \approx 10$ in the given cosmological framework. This is is a key result, since this kind of fermionic DM systems can provide a novel mechanism for SMBH formation in the early Universe, offering a possible solution to the yet open problem of how the first SMBHs observed have grown so massive so fast (see Fig. 3.3 evidencing the existence of a last stable configuration prior to the core-collapse into a SMBH, and Fig. 3.5 for the same result though shown through the more familiar *turning-point* criterium). A more thorough explanation of this important resut is available in Argüelles et al. (2021b).

The advantages of this kind of thermodynamic approaches is that it allows for a detailed description of the relaxed halos from the very center to periphery, not possible in N-body simulations due to finite inner-halo resolution. In addition, it includes richer physical ingredients such as (i) general relativity

— necessary for a proper gravitational DM core-collapse to a SMBH; (ii) the quantum nature of the particles — allowing for an explicit fermion mass dependence in the profiles; (iii) the Pauli principle self-consistently included in the phase-space distribution function — giving place to novel *core-halo* profiles at (violent) relaxation.

Our treatment allows to link the behavior and evolution of the DM particles from the early Universe all the way to the late stages of non-linear structure formation. We obtain the virial halo mass, $M_{\rm vir}$, with associated redshift $z_{\rm vir}$. The fermionic halos are assumed to be formed by fulfilling a maximum entropy production principle at virialization. It allows to obtain a most likely distribution function of Fermi-Dirac type, as first shown in Chavanis (1998) (generalizing Lynden-Bell results), here applied to explain DM halos. Finally, the stability, typical life-time of such equilibrium states, as well as their possible astrophysical applications, are studied within a thermodynamic approach.

We outline below all the main results and its astrophysical consequences.

We have calculated for the first time the caloric curves for self-gravitating, tidally-truncated matter distributions of $\mathcal{O}(10)$ keV fermions at finite temperatures, within general relativity. We applied this framework to realistic DM halos (i.e. sizes and masses). With the precise shape of the caloric curve, we establish the families of stable as well as astrophysical DM profiles (see Figs. 3.3 and 3.4). They are either King-like or develop a *core-halo* morphology able to fit the rotation curve in galaxies (Argüelles et al., 2018, 2019). In the first case, the fermions are in the dilute regime and correspond to a global maximum of entropy. In the second case, the degeneracy pressure (i.e. Pauli principle) is holding the quantum core against gravity, and correspond to a local maximum of entropy. Those metastable states are extremely long-lived and, as such, they are the more likely to arise in nature. Thus, these results prove that DM halos with a *core-halo* morphology are a very plausible outcome within nonlinear stages of structure formation.

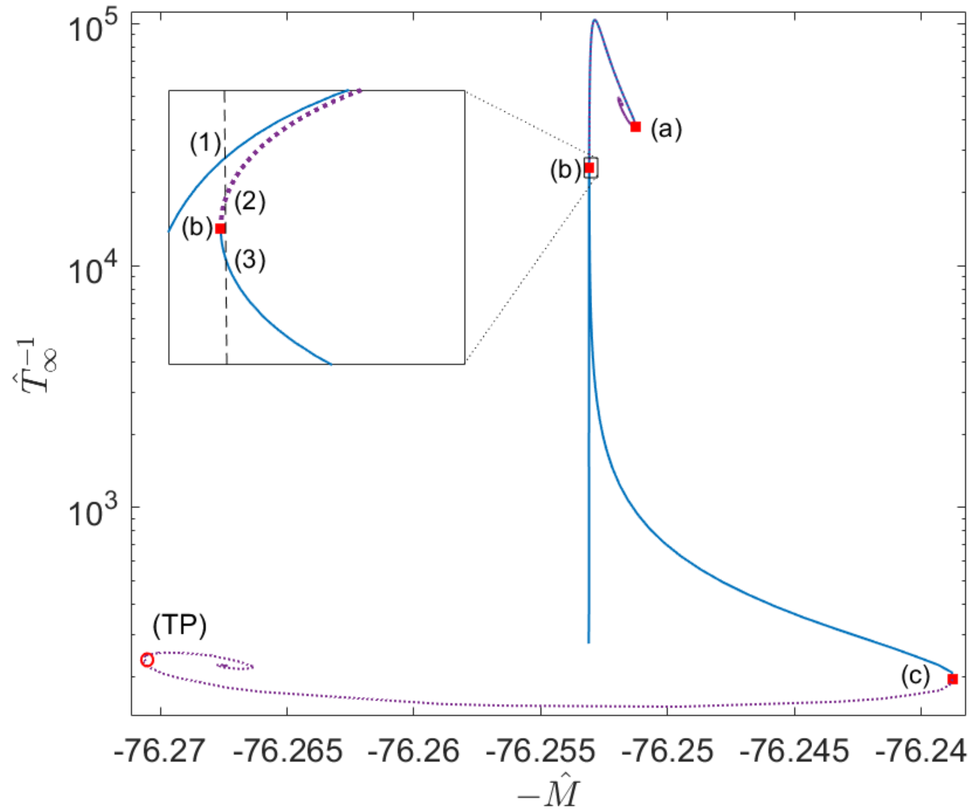

Figure 3.3: Series of equilibrium solutions along the caloric curve for tidally-truncated configurations of $mc^2 = 48$ keV fermions with fixed number of particles. The states within the continuous-blue branches are thermodynamically (and dynamically) stable (i.e. either local or global entropy maxima), while the dotted-violet branches - between (a) and (b) and after (c) - are unstable (i.e. either minimum or saddle point of entropy). Solution (3) is stable and fulfills with the virialization conditions. The arising of the second spiral of relativistic origin for high T_∞ is characteristic of caloric curves at fixed N within general relativity, and imply the existence of a turning point in a mass-central density curve. Taken from Argüelles et al. (2021b)

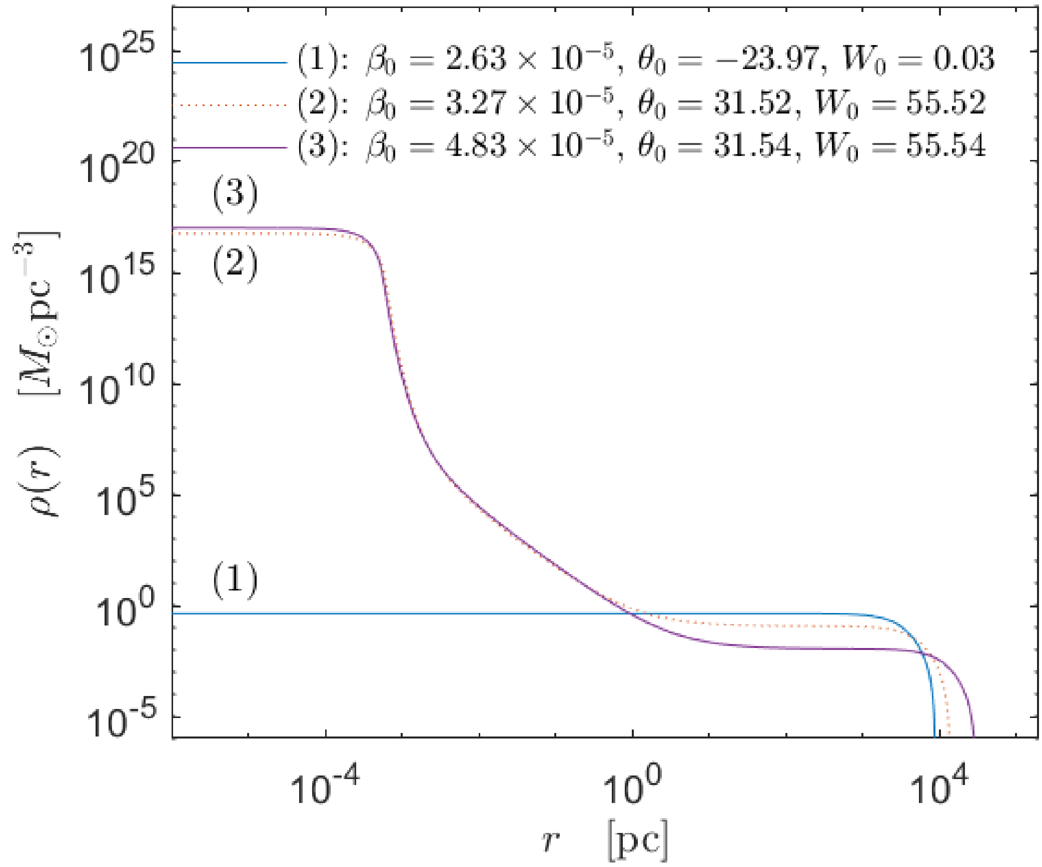

Figure 3.4: Density profiles for $mc^2 = 48$ keV corresponding with the equilibrium states of the caloric curve in Fig. 3.3 with corresponding fixed total halo mass. Only the profiles (1) (resembling a King distribution) and the *core-halo* one (3) are stable, while profile (2) is thermodynamically unstable. Interestingly, solutions like (3) were successfully applied to explain the DM halo in the Milky Way in Argüelles et al. (2018). They are stable, extremely long-lived and fulfill the observed surface DM density relation, as well as the expected value of the DM dispersion velocity. Taken from Argüelles et al. (2021b)

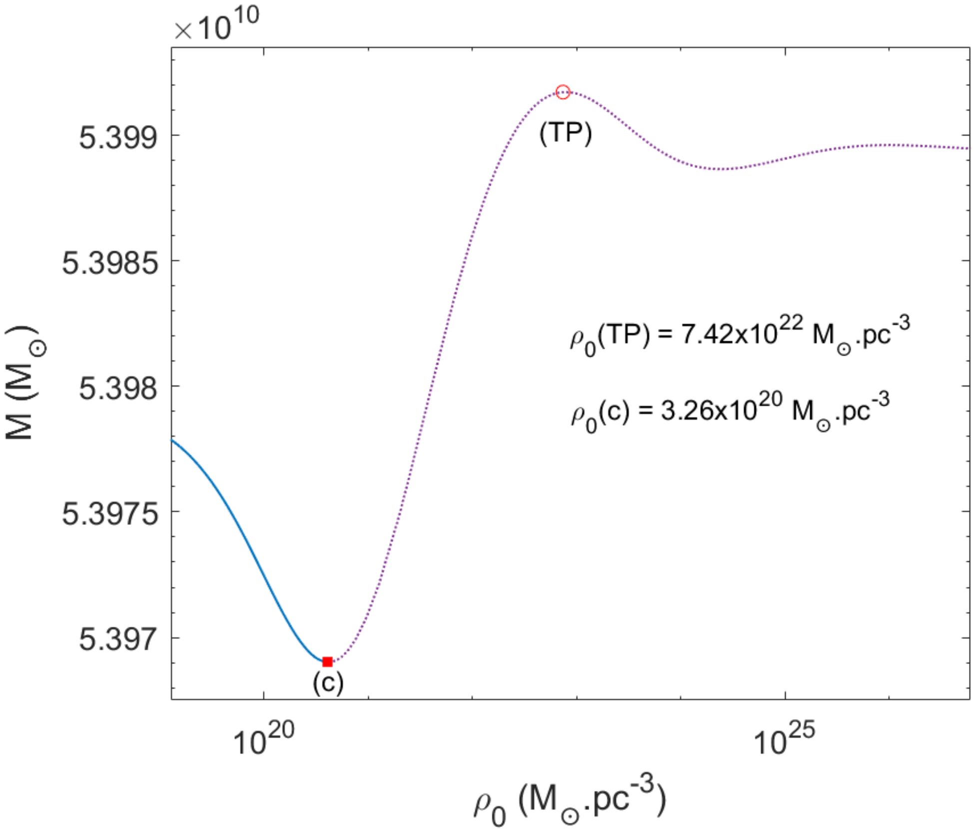

Figure 3.5: Series of equilibrium states with $N > N_{\rm OV}$ are shown along a ρ_0 vs. M curve, in correspondence with the caloric curve of Fig. 3.3. The last stable configuration at the onset of the core-collapse occurs at the minimum of this curve and *prior* to the turning point instability (corresponding with point (c) in Fig. 3.3). Such a critical solution has a critical core mass $M_c^{\rm cr} \approx 2 \times 10^8 M_\odot$, and thus a forming a SMBH from DM core-collapse. Figure taken from Ref. Argüelles et al. (2021b)

3.3 Interactions in Warm Dark Matter: A View from Cosmological Perturbation Theory

The traditional ΛCDM paradigm of cosmology is in remarkable agreement with large scale cosmological observations and galaxy properties. However, there is an increasing number of tensions of the ΛCDM with observations on smaller scales, such as the so-called "missing" DM sub-halo problem and the "core-cusp" discrepancy.

Specifically, high-resolution cosmological simulations of average-sized halos in ΛCDM predict an overproduction of small-scale structures, significantly larger that the observed number of small satellite galaxies in the Local Group. Moreover, N-body simulations of CDM predict a cuspy density profile for virialized halos, while observations show dwarf spheroidal galaxies (dSphs) having flattened smooth density profiles in their central regions.

A possible alternative to alleviate or try to resolve such tensions, is to consider *warm* dark matter particles (WDM), meaning that they are semi-relativistic during the earliest stages of structure formation with non-negligible free-streaming particle length.

WDM models feature an intermediate velocity dispersion between HDM and CDM that results in a suppression of structures at small scales due to free-streaming. If this free streaming scale today is smaller than the size of galaxy clusters, it can provide a solution to the missing satellites problem. However, thermally produced WDM suffers from the so called *catch-22* problem when studied within N-body simulations (Shao et al., 2013). Such WDM-only simulations either show unrealistic core-sizes for particle masses above the keV range, or they acquire the right halo sizes though for sub-keV masses, in direct conflict with phase-space and Lyman-α constraints.

Another compelling alternative to collisionless CDM, apart from WDM, is to consider interactions in CDM. This consideration relaxes the assumption that CDM interacts only gravitationally after early decoupling, and includes interactions either between DM and SM particles or additional hidden particles, or among DM particles themselves. These later models are denominated as "self-interacting" DM models (SIDM).

With the aim of shedding light into this matter, recently in Yunis et al. (2020) we have provided a general framework for self-interacting WDM in cosmological perturbations, by deriving from first principles a Boltzmann hierarchy which retains certain independence from a particular interaction Lagrangian. There, elastic interactions among the massive particles were considered, to obtain a hierarchy which is more general than the ones usually obtained for non-relativistic (as for cold DM) or for ultra-relativistic (as for neutrinos) approximations. The more general momentum-dependent kernel integrals in the Boltzmann collision terms are explicitly calculated for different field-mediator models, including a scalar field or a massive vector field.

In particular, if the Self Interactions maintain the DM fluid in kinetic equilibrium all the way until the fluid becomes non relativistic, the background distribution function at that moment will switch into a non relativistic form, constituting the scenario known as Non Relativistic Self Decoupling (a.k.a. late kinetic decoupling). The consequences of this scenario are poorly explored in the literature, and only some preliminary results have been recently obtained within simplified DM fluid approximations in Egana-Ugrinovic et al. (2021). However, more recently in Yunis et al. (2021) this late kinetic decoupling physics was fully explored, but this time with self-interactions treated from first principles interaction Lagrangians (i.e. superseeding the fluid-approximation), following the formalism developed in Yunis et al. (2020). There, it was found that, if one imposes continuity of the limiting expressions for the energy density, the non relativistic distribution function can be found in an analytic expression (see Yunis et al. (2021) for details).

Figure 3.6 illustrates the effects of self-interactions in the matter power spectrum for the case of a massive scalar field-mediator, while including for the late kintetic decoupling case. We have used an extended version of the CLASS code incorporating our results for SI-WDM with particle masses in the $\sim$ keV range. There, we see some of the particular features of the models. We see that the inclusion of Self Interactions, for models with Non Relativistic Self Decoupling (i.e. late kinetic decoupling), the resulting power spectra may differ significantly from its relativistic counterpart. Indeed, we find that in this regime the models are "colder" (i. e. as if they correspond to a higher particle mass), and show even at smaller k values a distinctive oscillatory pattern (see e.g. dot-dashed curves in Fig. 3.6. This indeed has the effect of increasing the amount of small structure formed for these models, implying that the few keV (traditional) WDM models which were excluded from phase-space arguments, can now be back to agreement with observations in this new SI-WDM scenarios.

Most of the tensions inherent to νMSM WDM models come from structure formation, namely MW satellite counts and Lyman-α observations. These are related to the fact that the preferred parameter ranges may underproduce small structure and almost rule out the available parameter space. So, the inclusion of Self Interactions can significantly relax the existing bounds on this family of models. Thus we are studying currently the evaluation of the predictions of these models for the number of MW satellites as well for the observations of the Lyman-α forest, results which will be presented in the next year.

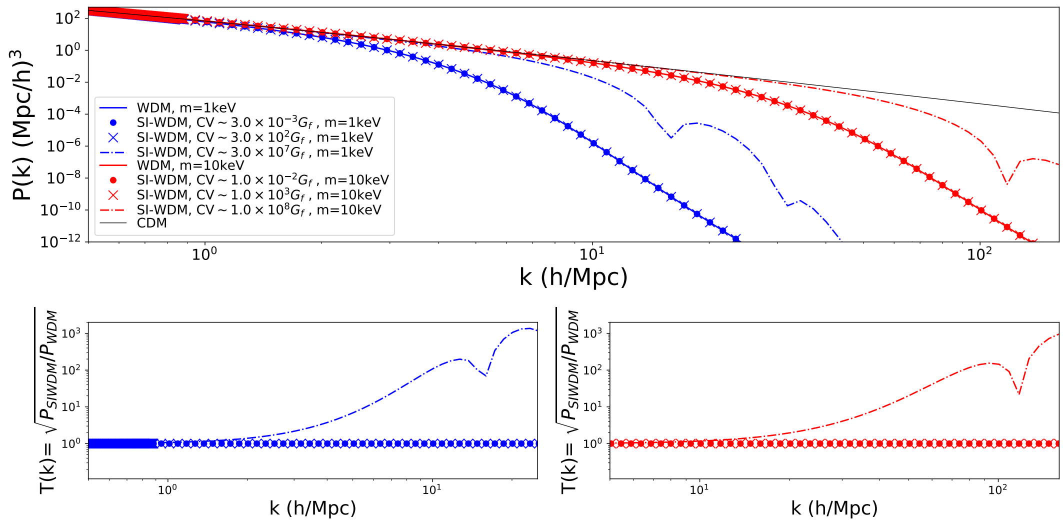

Figure 3.6: Power Spectrum (*top panel*) and Transfer Functions with respect to standard WDM (*bottom panels*) for a vector field SI-WDM model, using a modification to CLASS. We assume the relaxation time approximation, and consider two values of the DM particle mass: 1 and 10 keV. Also plotted are the power spectra of a CDM model and of WDM models with DM mass of 1 and 10 keV. All WDM and SI-WDM models consider a nonresonant production scenario (Dodelson-Widrow mechanism, Dodelson and Widrow (1993)) with $T \sim (4/11)^{1/3} T_\gamma$. Importantly, the effect of large enough self-interactions, increase the amount of small structure formed for these models (see dot-dashed curves), implying that the few keV (traditional) WDM models which were excluded in the past, can now be back to agreement with observations in this new SI-WDM scenarios. Reproduced from referenceYunis et al. (2021)

4 Publications 2021

1. Becerra-Vergara, E. A.; Argüelles, C. R.; Krut, A.; Rueda, J. A.; Ruffini, R., “Hinting a dark matter nature of Sgr A* via the S-stars”, Monthly Notices of the Royal Astronomical Society 505 (2021), issue 1, pp L64-L68.

   The motion data of the S-stars around the Galactic Centre gathered in the last 28 yr imply that Sgr A* hosts a supermassive compact object of about $4 \times 10^6\ M_\odot$, a result awarded with the Nobel Prize in Physics 2020. A non-rotating black hole (BH) nature of Sgr A* has been uncritically adopted since the S-star orbits agree with Schwarzschild geometry geodesics. The orbit of S2 has served as a test of general relativity predictions such as the gravitational redshift and the relativistic precession. The central BH model is, however, challenged by the G2 post-peripassage motion and by the lack of observations on event-horizon-scale distances robustly pointing to its univocal presence. We have recently shown that the S2 and G2 astrometry data are better fitted by geodesics in the spacetime of a self-gravitating dark matter core-halo distribution of 56 keV-fermions, ’darkinos’, which also explains the outer halo Galactic rotation curves. This letter confirms and extends this conclusion using the astrometry data of the 17 best-resolved S-stars, thereby strengthening the alternative nature of Sgr A* as a dense core of darkinos.

2. Argüelles, Carlos R.; Mestre, M. F.; Becerra-Vergara, E. A.; Crespi, V.; Krut, A.; Rueda, J. A.; Ruffini, R., “What does lie at the Milky Way centre? Insights from the S2 star orbit precession”, Monthly Notices of the Royal Astronomical Society, accepted for pubblication (2021), doi:10.1093/mnrasl/slab126.

   It has been recently demonstrated that both, a classical Schwarzschild black hole (BH), and a dense concentration of self-gravitating fermionic dark matter (DM) placed at the Galaxy centre, can explain the precise astrometric data (positions and radial velocities) of the S-stars orbiting Sgr A*. This result encompasses the 17 best resolved S-stars, and includes the test of general relativistic effects such as the gravitational redshift in the S2-star. In addition, the DM model features another remarkable result: the dense core of fermions is the central region of a continuous density distribution of DM whose diluted halo explains the Galactic rotation curve. In this Letter, we complement the above findings by analyzing in both models the relativistic periapsis precession of the S2-star orbit. While the Schwarzschild BH scenario predicts a unique prograde precession for S2, in the DM scenario it can be either retrograde or prograde, depending on the amount of DM mass enclosed within the S2 orbit, which in turn is a function of the DM fermion mass. We show that all the current and publicly available data of S2 can not discriminate between the two models, but upcoming S2 astrometry close to next apocentre passage could potentially establish if Sgr A* is governed by a classical BH or by a quantum DM system.

3. Argüelles, Carlos R.; Díaz, Manuel I.; Krut, Andreas; Yunis, Rafael, "On the formation and stability of fermionic dark matter halos in a cosmological framework", Monthly Notices of the Royal Astronomical Society 502 (2021), issue 3, pp 4227-4246.

   The formation and stability of collisionless self-gravitating systems is a long standing problem, which dates back to the work of D. Lynden-Bell on violent relaxation, and extends to the issue of virialization of dark matter (DM) halos. An important prediction of such a relaxation process is that spherical equilibrium states can be described by a Fermi-Dirac phase-space distribution, when the extremization of a coarse-grained entropy is reached. In the case of DM fermions, the most general solution develops a degenerate compact core surrounded by a diluted halo. As shown recently, the latter is able to explain the galaxy rotation curves while the DM core can mimic the central black hole. A yet open problem is whether this kind of astrophysical core-halo configurations can form at all, and if they remain stable within cosmological timescales. We assess these issues by performing a thermodynamic stability analysis in the microcanonical ensemble for solutions with given particle number at halo virialization in a cosmological framework. For the first time we demonstrate that the above core-halo DM profiles are stable (i.e. maxima of entropy) and extremely long lived. We find the existence of a critical point at the onset of instability of the core-halo solutions, where the fermion-core collapses towards a supermassive black hole. For particle masses in the keV range, the core-collapse can only occur for $M_{vir} \geq 10^9 M_\odot$ starting at $z_{vir} = 10$ in the given cosmological framework. Our results prove that DM halos with a core-halo morphology are a very plausible outcome within nonlinear stages of structure formation.

4. Yunis, R. I; Argüelles, C. R., Scóccola, C. G.; Nacir, D. L.; Giordano, G."Self Interactions in Warm Dark Matter: A View from Cosmological Perturbation Theory", Astronomy Reports 65 (2021) issue 10, pp 1068-1073

   We provide a short overview into Self Interacting Warm Dark Matter (SI-WDM) models from the context of Cosmological Perturbation Theory (CPT). The aim is to generalize conventional Cold DM models, by proposing a more general framework both from theoretical as well as from numerical fronts, on the effects of SI-WDM on the linear power spectrum and its consequent imprints on non-linear structure formation. After describing the theoretical background, we present useful analytic expressions for the collision terms in the Boltzmann Hierarchies, and provide some numerical results within the Relaxation Time Approximation (RTA). We consider massive DM particles that decouple from the hot plasma while relativistic. We introduce elastic DM-DM interactions under an ansatz for the scattering amplitude that accounts for massive mediators on an effective way. Paying special attention to the self interaction decoupling mechanisms, we analyze scenarios where the particle undergoes self decoupling while relativistic as well as while non relativistic.

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