Self-gravitating Systems of Dark Matter Particles

Contents

1 Topics **1137**

2 Participants **1139**
2.1 ICRANet 1139
2.2 External on going collaborations 1139
2.3 Graduate Students 1140

3 Highlighted Publications 2020 **1141**
3.1 Fermionic dark matter and galactic structures 1141
3.2 Galactic Center constraints on self-interacting sterile neutrino dark matter 1146
3.3 Boltzmann hierarchies for self-interacting warm dark matter scenarios 1149
3.4 Formation and stability of fermionic dark matter halos in a cosmological framework 1152

4 Publications 2020 **1157**

Bibliography **1161**

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.

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3 Highlighted Publications 2020

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) 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 we move forward by performing in Becerra-

Vergara et al. (2020) an observational test of the theoretically predicted existence of the dense quantum core at the Galactic center within the DM-RAR model. Namely, to test whether the quantum core of the DM could work as an alternative to the SMBH scenario for SgrA*. For this task, the explanation of the multiyear accurate astrometric data of the S2 star around Sgr A*, including the relativistic redshift that has recently been verified, is particularly important. Another relevant object is G2, whose most recent observational data, as we have recalled, challenge the scenario of a SMBH.

We show in Becerra-Vergara et al. (2020) that the solely gravitational potential of such a DM profile for a fermion mass of 56 keV explains:

1. all the available time-dependent data of the position (orbit) and line-of-sight radial velocity (redshift function z) of S2,

2. the combination of the special and general relativistic redshift measured for S2,

3. the currently available data on the orbit and z of G2,

4. its post-pericenter passage deceleration without introducing a drag force.

For both objects, it was found that the RAR model fits the data better than the BH scenario. The reduced chi-squares of the time-dependent orbit and z data are $\langle\bar{\chi}^2\rangle_{\rm S2,RAR} \approx 3.1$ and $\langle\bar{\chi}^2\rangle_{\rm S2,BH} \approx 3.3$ for S2 and $\langle\bar{\chi}^2\rangle_{\rm G2,RAR} \approx 20$ and $\langle\bar{\chi}^2\rangle_{\rm G2,BH} \approx 41$ for G2. The fit of the z data shows that, while for S2 the fits are comparable, i.e. $\bar{\chi}^2_{z,\rm RAR} \approx 1.28$ and $\bar{\chi}^2_{z,\rm BH} \approx 1.04$, for G2 only the RAR model fits the data: $\bar{\chi}^2_{z,\rm RAR} \approx 1.0$ and $\bar{\chi}^2_{z,\rm BH} \approx 26$. See details in Figs. 3.1, 3.2 and 3.3.

Therefore, to summarize, it has been shown that the sole DM core, for 56 keV *darkinos*, explains the orbits of S2 and G2. No drag force nor other external agents are needed, i.e. their motion is purely geodesic. Our group is currently working on an extension of this work by analyzing all the existing observational data of the S-cluster stars, namely the orbit and velocity data of 17 stars. We expect to publish these novel results in a new article and will be presented in the Scientific Report of the year 2021.

A further very interesting consequence of this scenario is that, a core made of these *darkinos*, becomes unstable against gravitational collapse into a BH for a 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 as such is also being studied by our group.

This work has been one of the most important results of ICRANet in 2020. The fact that the center of our galaxy could harbor a concentration of DM instead of a SMBH has attracted worldwide attention. A Press Release was published in the Astronomy & Astrophysics journal:

https://www.aanda.org/2020-press-releases/1880

It is also worth to mention the award *Premio Estímulo en Astronomía "Dr. Jorge Sahade"*, received by Dr. Carlos R. Argüelles in Argentina, delivered by the National Academy of Physical and Natural Sciences, which recognized the importance of his works in the field of DM:

https://laplata.conicet.gov.ar/la-academia-nacional-de-ciencias-exactas-fisicas-y-naturales-distingue-a-un-investigador-del-conicet-la-plata/

Furthermore, the not-scientific audience has been also attracted by these novelties; indeed the major newspaper in Colombia, "El Tiempo", dedicated a special article on September 9, 2020, to our results:

https://www.eltiempo.com/vida/ciencia/que-hay-en-el-centro-de-la-galaxia-investigadores-aseguran-que-podria-ser-materia-oscura-536640

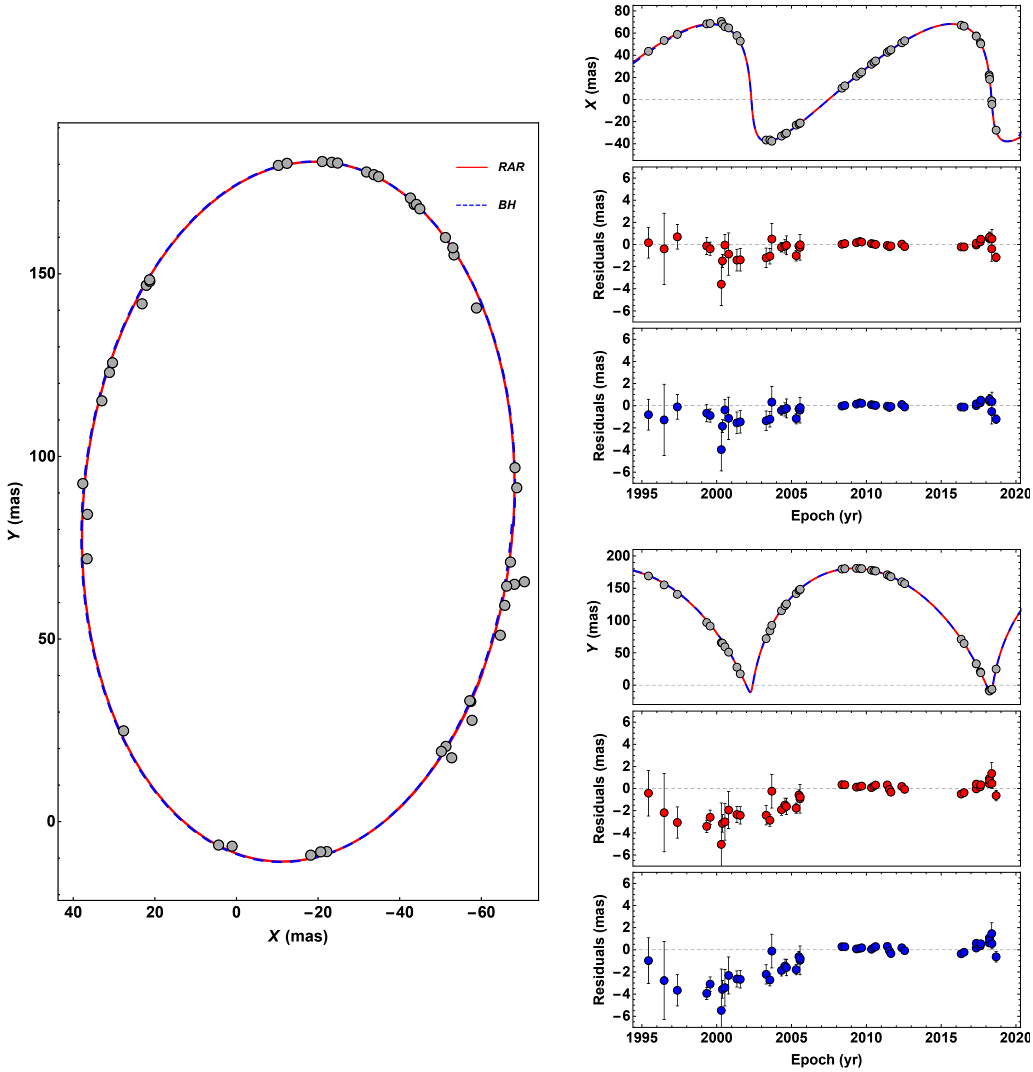

Figure 3.1: Theoretical (central BH and RAR models) and observed orbit of S2 around Sgr A*. The left panel shows the orbit, i.e. the right ascension (X) vs. declination (Y), while the right panel shows X and Y vs. observation time, with the corresponding residuals of the best-fit for the BH (blue) and the RAR (red) models. The theoretical models are calculated by solving the equations of motion of a test particle in the gravitational field of: 1) a Schwarzschild BH of $4.075 \times 10^6\ M_\odot$, and 2) the DM-RAR model for 56 keV-fermions (leading to a quantum core mass $3.5 \times 10^6\ M_\odot$). Taken from Becerra-Vergara et al. (2020).

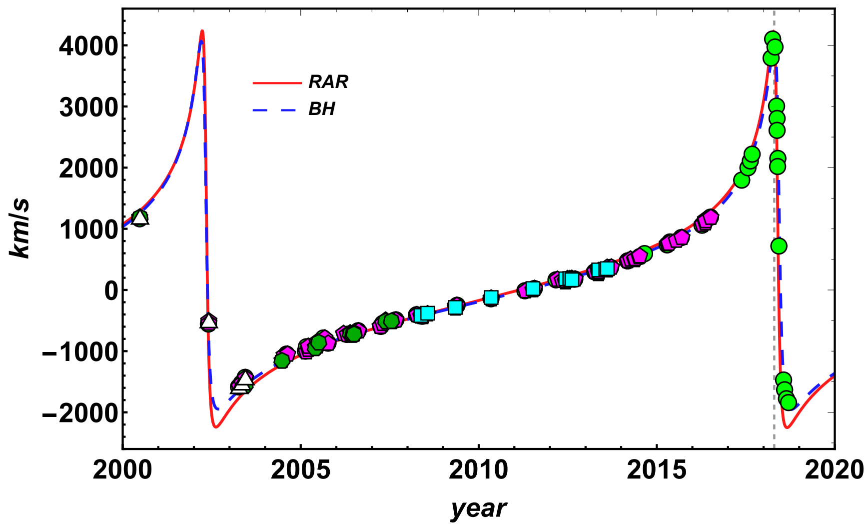

Figure 3.2: Theoretical and observed line-of-sight radial velocity for S2, calculated for the same models as in Fig. 3.1. Both models can fit the data with similar precision. Taken from Becerra-Vergara et al. (2020).

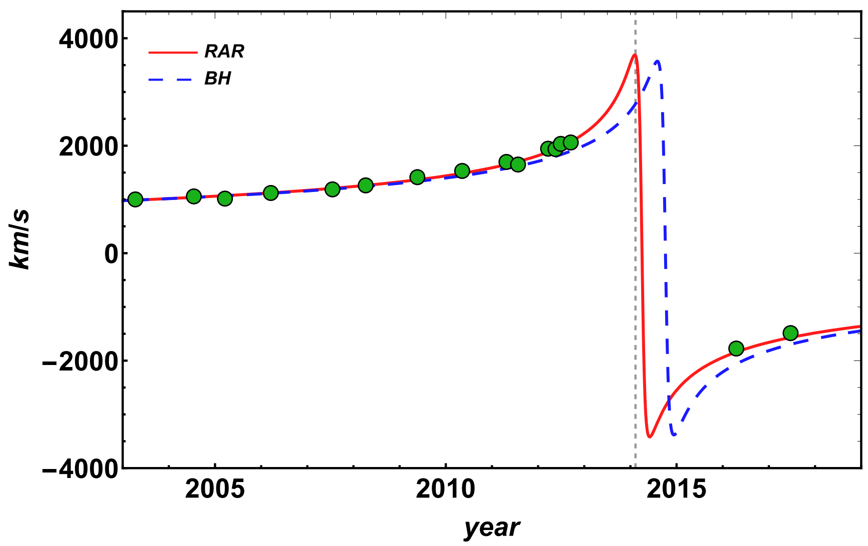

Figure 3.3: Theoretical and observed line-of-sight radial velocity for G2, calculated for the same models as in Fig. 3.1. The RAR model can fit the data with noticeably better precision than the BH. Taken from Becerra-Vergara et al. (2020).

3.2 Galactic Center constraints on self-interacting sterile neutrino dark matter

On the other side, the topic of self-interacting DM, namely DM particles interacting among themselves via some unknown fundamental interaction besides gravity, is a very active field of research within the DM community. Self-interacting DM (SIDM) has been proposed as a possible solution to a number of challenges which is facing the standard cosmological model on galactic scales. This year, two different works in this field were published by our group (within different international collaborations).

In 2016, our group have presented an extension of the RAR model to include fermion self-interactions, it is referred to as the Argüelles, Mavromatos, Rueda and Ruffini (AMRR) model (Argüelles et al., 2016). In the AMRR model, it has been advanced that the *darkinos* might be the right-handed sterile neutrinos introduced in the minimum standard model extension (νMSM) paradigm (Shaposhnikov, 2008). The AMRR model adopts right-handed neutrinos self-interacting via dark-sector massive (axial) vector mediators.

In 2020, our group explored in Yunis et al. (2020a) the radiative decay channel of such sterile neutrinos into X-rays, due to the Higgs portal interactions of the νMSM. First, this work shows that such generalized RAR profiles, namely the ones obtained including fermion self-interactions, are in good agreement with the overall Milky Way rotation curve. In addition, it has been identified the window of self-interacting DM cross-sections that satisfy the known bullet cluster constraints.

In order to further constrain the AMRR-νMSM model, Yunis et al. (2020a) performed an indirect detection analysis using X-ray observations from the Galactic center taken by the Nustar mission. A summarizing plot of all observational constraints is shown in Fig. 3.4.

It has been also advanced a new generation mechanism, based on vector-meson decay, able to produce these sterile neutrinos in the early Universe.

In summary, by considering a DM profile that self-consistently accounts for the particle physics model, our group has performed a new analysis of NuSTAR X-ray data to study how the νMSM parameter-space constraints are affected by self-interactions among sterile neutrinos. In particular, we have shown how standard production mechanisms in the early Universe can be affected through a decay of the massive vector field that acts as the mediator of the self-interactions of the DM candidates, which could broaden the allowed

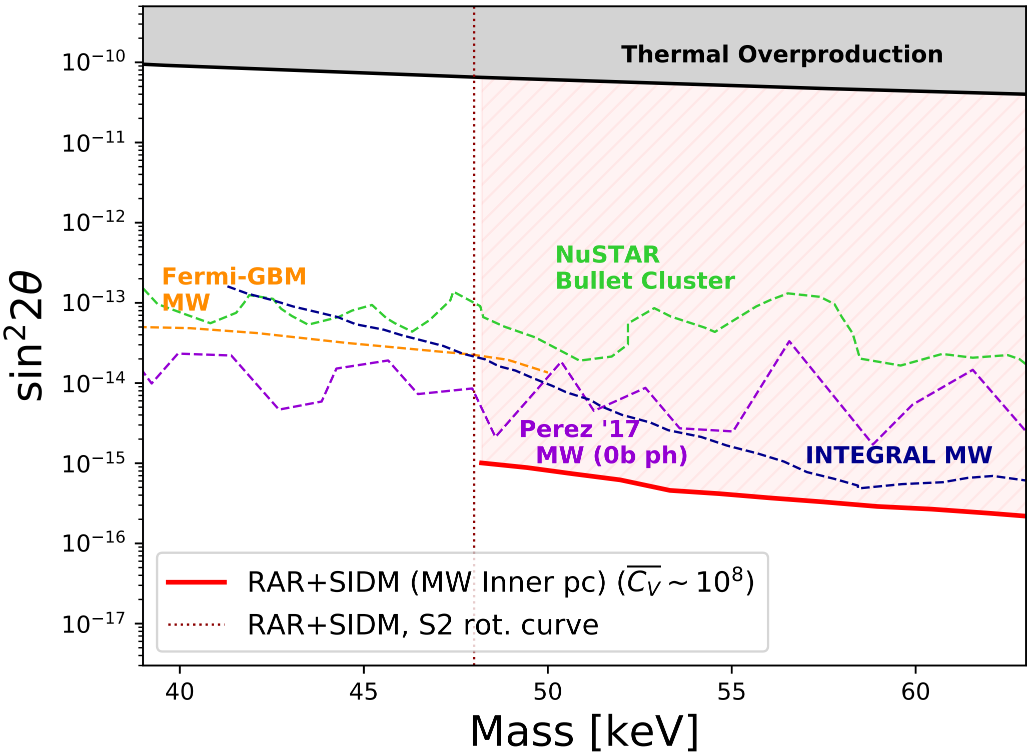

Figure 3.4: Sterile neutrino parameter space limits obtained for Galactic Center observations using the AMRR profiles (continuous red line), when assuming DM production due to self-interactions through a massive vector field mediator. The light-red shaded region above the continuous red line corresponds to the AMRR limits given by X-ray bounds (i.e. indirect detection analysis), while the vertical shaded region below 48 keV indicates the smallest DM mass compatible with S-cluster stars' rotation curve data (Yunis et al., 2020a). The upper shaded region corresponds to production mechanism bounds: non-resonant production under no lepton asymmetry. Other dotted lines refer to several X-ray bounds for different DM halo profiles including 0-bounce photon analysis.

parameter space with respect to standard νMSM.

3.3 Boltzmann hierarchies for self-interacting warm dark matter scenarios

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 singular 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 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, in Yunis et al. (2020b) 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 La-grangian. We consider elastic interactions among the massive particles, and 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.

As an application, we have studied the evolution of the interaction rate per particle under the relaxation time approximation, and assess when a given self-interaction is relevant in comparison with the Hubble expansion rate. Our framework aims to be a useful tool to evaluate DM self-interaction effects in the linear power spectrum, with the consequent imprints on non-linear scales of structure formation. Figure 3.5 illustrates the effects of self-interactions in the matter power spectrum for the case of a massive scalar field-mediator. We have used an extended version of the CLASS code incorporating our results for SI-WDM with particle masses in the $\sim$ keV range.

In order to compare the results for standard CDM, WDM and the SI-WDM model, both WDM and SI-WDM components were assumed to have a relativistic Fermi-Dirac equilibrium distribution function f_0 with a given temperature T_{dec} (i.e. a distribution function that corresponds to relativistic decoupled thermal relics), and their abundances were adjusted to match that of CDM in the best fit data from the Planck mission (2018).

The power spectra of Fig. 3.5 show that for weaker interactions the results are practically indistinguishable from standard WDM. It is only for the cases of higher coupling constants (where the relativistic decoupling assumption is no longer valid) that new features appear: both the modification in the transfer functions obtained in Hannestad and Scherrer (2000), and acoustic oscillations at higher k reminiscent of fluid approximations. Such results are explicitly shown in dashed or dot-dashed lines in Fig. 3.5, for given self-interaction strengths either for the case of $m = 1$ keV and $m = 10$ keV.

For the case of $m \sim$ few keV as of typical WDM models under the thermal decoupling assumption Lovell et al. (2014), it can be seen that our SI-WDM power spectra do not exhibit the steep trend at large k typical of those standard WDM scenarios. This less abrupt suppression of power at typical (comoving) wave numbers of $k \sim 10$ h/Mpc (i.e. short scales relevant for sub-halo structures), can be better visualized in the transfer function of Fig. 3.5 (bottom pannel). Such an effect should point to a better agreement with small-scale structure constraints for the lower end of the (thermal relic) keV particle-mass range. All in all, a more general behaviour of the suppression in the power spectrum (relevant for sub-structure number counts), together with the self-interacting nature of the $\sim$ keV DM candidates (relevant to the inner shape of DM halos), could bring the SI-WDM paradigm into an appealing alternative to the CDM paradigm.

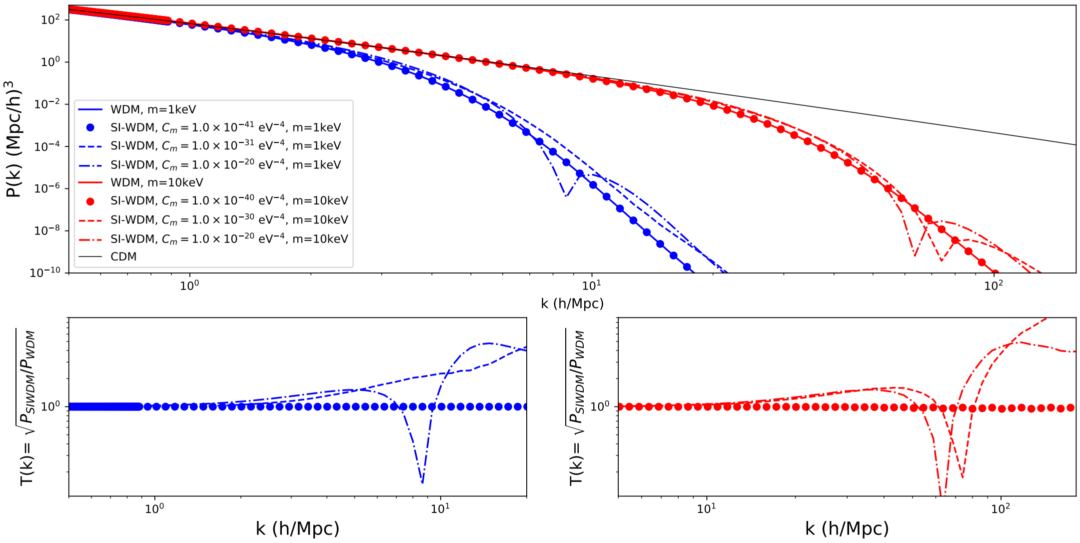

Figure 3.5: Power Spectrum (*top panel*) and Transfer Functions with respect to standard WDM (*bottom panels*) for a massive scalar SI-WDM model under the relaxation time approximation, for two values of the DM particle mass: 1 and 10 keV. Also plotted are the power spectra of CDM and of a 1 and 10 keV WDM model. Notice all the calculations assume relativistic interaction decoupling, however dashed and dashed-dotted lines refer to coupling strengths which do not fulfill this hypothesis and should undergo non relativistic self-interaction decoupling.

3.4 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., 2020).

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. Our results prove that DM halos with a *core-halo* morphology are a very plausible outcome within nonlinear stages of structure formation.

The advantages of our approach 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. 3.6 and 3.7). 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.

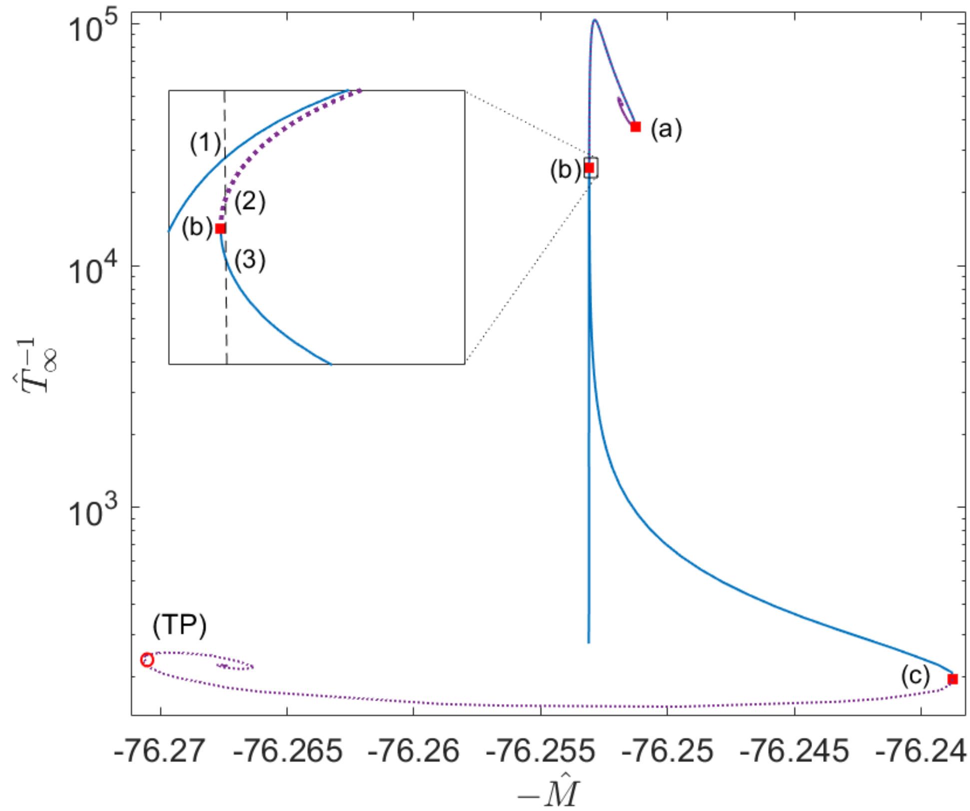

Figure 3.6: Series of equilibrium solutions along the caloric curve for tidally-truncated configurations of $mc^2 = 48$ keV fermions with fixed number of particles. The states within the continuous-blue branches are thermodynamically (and dynamically) stable (i.e. either local or global entropy maxima), 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. (2020).

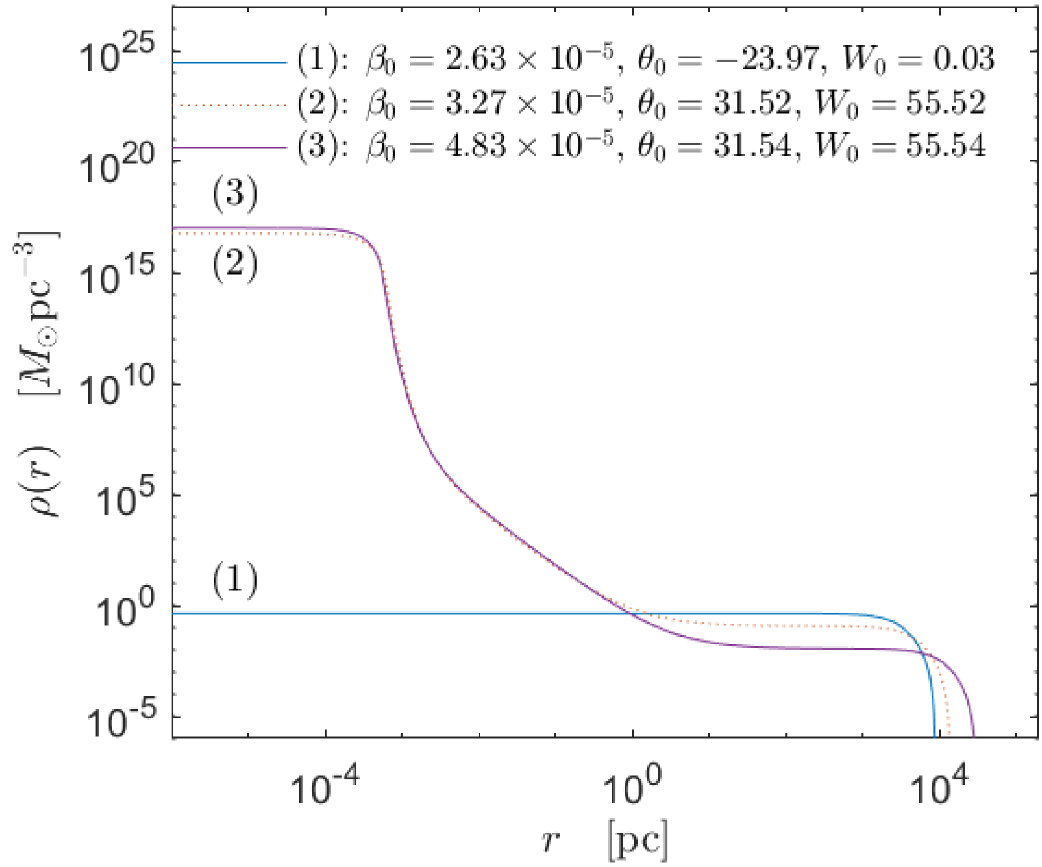

Figure 3.7: Density profiles for $mc^2 = 48$ keV corresponding with the equilibrium states of the caloric curve in Fig. 3.6 with corresponding fixed total halo mass. Only the profiles (1) (resembling a King distribution) and the *core-halo* one (3) are stable, while profile (2) is thermodynamically unstable. 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. (2020).

4 Publications 2020

1. Yunis, R.; Argüelles, C. R.; Mavromatos, N. E.; Moliné, A.; Krut, A.; Carinci, M.; Rueda, J. A.; Ruffini, R., "Galactic center constraints on self-interacting sterile neutrinos from fermionic dark matter ("ino") models", Physics of the Dark Universe 30 (2020), article id. 100699.

   The neutrino minimal standard model (νMSM) has been tightly constrained in the recent years, either from dark matter (DM) production or from X-ray and small-scale observations. However, current bounds on sterile neutrino DM can be significantly modified when considering a νMSM extension, in which the DM candidates interact via a massive (axial) vector field. In particular, standard production mechanisms in the early Universe can be affected through the decay of such a massive mediator. We perform an indirect detection analysis to study how the νMSM parameter-space constraints are affected by said interactions. We compute the X-ray fluxes considering a DM profile that self-consistently accounts for the particle physics model by using an updated version of the Ruffini-Argüelles-Rueda (RAR) fermionic ("ino") model, instead of phenomenological profiles such as the Navarro-Frenk-White (NFW) distribution. We show that the RAR profile accounting for interacting DM, is compatible with measurements of the Galaxy rotation curve and constraints on the DM self-interacting cross section from the Bullet cluster. A new analysis of the X-ray NuSTAR data in the central parsec of the Milky Way, is here performed to derive constraints on the self-interacting sterile neutrino parameter-space. Such constraints are stronger than those obtained with commonly used DM profiles, due to the dense DM core characteristic of the RAR profiles.

2. Yunis, Rafael; Argüelles, Carlos R.; López Nacir, Diana, "Boltzmann hierarchies for self-interacting warm dark matter scenarios", Journal of Cosmology and Astroparticle Physics, Issue 09, article id. 041 (2020).

   We provide a general framework for self-interacting warm dark matter (WDM) in cosmological perturbations, by deriving from first principles a Boltzmann hierarchy which retains certain independence from a particular interaction La-grangian. We consider elastic interactions among the massive particles, and 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 examples of a scalar field or a massive vector field. As an application, we study the evolution of the interaction rate per particle under the relaxation time approximation, and assess when a given self-interaction is relevant in comparison with the Hubble expansion rate. Our framework aims to be a useful tool to evaluate DM self-interaction effects in the linear power spectrum, with the consequent imprints on non-linear scales of structure formation.

3. Becerra-Vergara, E. A.; Argüelles, C. R.; Krut, A.; Rueda, J. A.; Ruffini, R., "Geodesic motion of S2 and G2 as a test of the fermionic dark matter nature of our Galactic core", A&A 641 (2020) id.A34, 14 pp.

   The motion of S-stars around the Galactic center implies that the central gravitational potential is dominated by a compact source, Sagittarius A* (Sgr A*), which has a mass of about $4 \times 10^6\ M_\odot$ and is traditionally assumed to be a massive black hole (BH). The explanation of the multiyear accurate astrometric data of the S2 star around Sgr A*, including the relativistic redshift that has recently been verified, is particularly important for this hypothesis and for any alternative model. Another relevant object is G2, whose most recent observational data challenge the scenario of a massive BH: its post-pericenter radial velocity is lower than expected from a Keplerian orbit around the putative massive BH. This scenario has traditionally been reconciled by introducing a drag force on G2 by an accretion flow. As an alternative to the central BH scenario, we here demonstrate that the observed motion of both S2 and G2 is explained in terms of the *dense core – diluted halo* fermionic dark matter (DM) profile, obtained from the fully relativistic Ruffini-Argüelles-Rueda (RAR) model. It has previously been shown that for fermion masses 48–350 keV, the RAR-DM profile accurately fits the rotation curves of the Milky Way halo. We here show that the solely gravitational potential of such a DM profile for a fermion mass of 56 keV explains 1) all the available time-dependent data of the position (orbit) and line-of-sight radial velocity (redshift function z) of S2, 2) the combination of the special and general relativistic redshift measured for S2, 3) the currently available data on the orbit and z of G2, and 4) its post-pericenter passage deceleration without introducing a drag force. For both objects, we find that the RAR model fits the data better than the BH scenario: the mean of reduced chi-squares of the time-dependent orbit and z data are $\langle\bar{\chi}^2\rangle_{\mathrm{S2,RAR}} \approx 3.1$ and $\langle\bar{\chi}^2\rangle_{\mathrm{S2,BH}} \approx 3.3$ for S2 and $\langle\bar{\chi}^2\rangle_{\mathrm{G2,RAR}} \approx 20$ and $\langle\bar{\chi}^2\rangle_{\mathrm{G2,BH}} \approx 41$ for G2. The fit of the corresponding z data shows that while for S2 we find comparable fits, that is, $\bar{\chi}^2_{z,\mathrm{RAR}} \approx 1.28$ and $\bar{\chi}^2_{z,\mathrm{BH}} \approx 1.04$, for G2 the RAR model alone can produce an excellent fit of the data, that is, $\bar{\chi}^2_{z,\mathrm{RAR}} \approx 1.0$ and $\bar{\chi}^2_{z,\mathrm{BH}} \approx 26$. In addition, the critical mass for gravitational collapse of a degenerate 56 keV-fermion DM core into a BH is $\sim 10^8\ M_\odot$. This result may provide the initial seed for the formation of the observed central supermassive BH in active galaxies, such as M87.

4. 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, in press (2020).

   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.

Bibliography

ARGÜELLES, C.R., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪Novel constraints on fermionic dark matter from galactic observables I: The Milky Way≫.
Phys. Dark Universe, **21**, pp. 82–89 (2018).

ARGÜELLES, C.R., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪Novel constraints on fermionic dark matter from galactic observables II: Galaxy scaling relations≫.
Phys. Dark Universe, **24**, 100278 (2019).

ARGÜELLES, C.R., MAVROMATOS, N.E., RUEDA, J.A. AND RUFFINI, R.
≪The role of self-interacting right-handed neutrinos in galactic structure≫.
JCAP, **1604(04)**, p. 038 (2016).

ARGÜELLES, C.R., DÍAZ, M.I., KRUT, A. AND YUNIS, R.
≪On the formation and stability of fermionic dark matter halos in a cosmological framework≫.
Monthly Notices of the Royal Astronomical Society (2020).

BECERRA-VERGARA, E.A., ARGÜELLES, C.R., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪Geodesic motion of S2 and G2 as a test of the fermionic dark matter nature of our Galactic core≫.
Astronomy & Astrophysics, **641**, A34 (2020).

CHAVANIS, P.H.
≪Generalized thermodynamics and kinetic equations: Boltzmann, Landau, Kramers and Smoluchowski≫.
Physica A Statistical Mechanics and its Applications, **332**, pp. 89–122 (2004).

CHAVANIS, P.H.
≪On the 'coarse-grained' evolution of collisionless stellar systems≫.
Monthly Notices of the Royal Astronomical Society, **300(4)**, pp. 981–991 (1998).

GAO, J.G., MERAFINA, M. AND RUFFINI, R.
≪The semidegenerate configurations of a selfgravitating system of fermions≫.
Astronomy & Astrophysics, **235**, pp. 1–7 (1990).

HANNESTAD, S. AND SCHERRER, R.J.
≪Selfinteracting warm dark matter≫.
Phys. Rev., **D62**, p. 043522 (2000).

KING, I.R.
≪The structure of star clusters. III. Some simple dynamical models≫.
Astronomical Journal, **71**, p. 64 (1966).

LOVELL, M.R., FRENK, C.S., EKE, V.R., JENKINS, A., GAO, L. AND THEUNS, T.
≪The properties of warm dark matter haloes≫.
Mon. Not. Roy. Astron. Soc., **439**, pp. 300–317 (2014).

LYNDEN-BELL, D.
≪Statistical mechanics of violent relaxation in stellar systems≫.
Monthly Notices of the Royal Astronomical Society, **136**, p. 101 (1967).

MICHIE, R.W.
≪On the distribution of high energy stars in spherical stellar systems≫.
Monthly Notices of the Royal Astronomical Society, **125**, p. 127 (1963).

RUFFINI, R., ARGÜELLES, C.R. AND RUEDA, J.A.
≪On the core-halo distribution of dark matter in galaxies≫.
Mon. Not. R. Astron. Soc., **451**, pp. 622–628 (2015).

RUFFINI, R. AND STELLA, L.
≪On semi-degenerate equilibrium configurations of a collisionless self-gravitating Fermi gas≫.
Astronomy & Astrophysics, **119**, pp. 35–41 (1983).

SHAO, S., GAO, L., THEUNS, T. AND FRENK, C.S.
≪The phase-space density of fermionic dark matter haloes≫.
Monthly Notices of the Royal Astronomical Society, **430(3)**, p. 2346–2357 (2013).
ISSN 0035-8711.

SHAPOSHNIKOV, M.
≪The nuMSM, leptonic asymmetries, and properties of singlet fermions≫.
JHEP, **08**, p. 008 (2008).

YUNIS, R., ARGÜELLES, C.R., MAVROMATOS, N.E., MOLINÉ, A., KRUT, A., CARINCI, M., RUEDA, J.A. AND RUFFINI, R.
≪Galactic center constraints on self-interacting sterile neutrinos from fermionic dark matter ("ino") models≫.
Physics of the Dark Universe, **30**, 100699 (2020a).

YUNIS, R., ARGÜELLES, C.R. AND LÓPEZ NACIR, D.
≪Boltzmann hierarchies for self-interacting warm dark matter scenarios≫.
Journal of Cosmology and Astroparticle Physics, **2020(9)**, 041 (2020b).