Self-gravitating Systems of Dark Matter Particles

Contents

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.

More recently, in Ruffini et al. (2015); Argüelles et al. (2018) such a quantum (fermionic) nature of the DM particles was incorporated in the phenomenology of galactic halos (not feasible in standard N-body simulations) within the so called Ruffini-Argüelles-Rueda (RAR) model. It self-consistently considers the Pauli exclusion principle yielding a quantum pressure that dominates over the central region of the configurations, which are surrounded by a more diluted halo composed of the same particles. As a result, the model predicts novel DM density profiles with a *dense core–diluted halo* morphology that depends on the fermion mass. On the observational side, distributions with fermion masses in the range of $\sim 50 - 350\,\mathrm{keV}$ which naturally account for the large-scale structure of the Universe, can also explain the galaxy rotation curves in different types of galaxies (Argüelles et al., 2018, 2019; Krut et al., 2023). At the same time, the degenerate fermion core residing at the halo center can mimic their central BHs (Argüelles et al., 2018, 2019; Becerra-Vergara et al., 2020, 2021; Argüelles et al., 2021, 2022b,a), or eventually collapse into one as demonstrated in Argüelles et al. (2021, 2023b, 2024) from general-relativistic stability criteria.

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.

Specific topics treated in 2024 together with the number of papers published on each topic are:

- DM in the Milky Way (3 papers).
- Supermassive black holes: its nature and formation channels (2 papers).

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3 Highlighted Publications 2024

3.1 Dark matter in the Milky Way

3.1.1 Stellar streams and S-stars: powerful tracers of the overall gravitational potential

In Mestre et al. (2024), we modeled the GD-1 stellar stream of the Milky Way using a spherical core-halo DM distribution according to the extended RAR model that simultaneously explains the dynamics of the S-cluster stars through its degenerate fermion core without assuming a central BH. We used two optimization algorithms to fit the initial conditions of the stream orbit and the fermionic model. We modeled the baryonic potential with a bulge and two disks (thin and thick) with fixed parameters according to the recent literature. The stream observables were 5D phase-space data from the Gaia DR2 survey. Interestingly, we found good fits for the GD-1 stream and the S-stars for a family of fermionic core-halo profiles parameterized by the fermion mass. The particle masses are constrained in the range 56 keV/c^2, with a corresponding DM core of $\sim 10^3$ Schwarzschild radii, to 360 keV/c^2, which corresponds to the most compact core of 5 Schwarzschild radii before the gravitational collapse into a BH of approximately $4 \times 10^6 M_\odot$.

This work provides evidence that the fermionic profile is a reliable model for the massive central object and the DM of the Galaxy. Remarkably, this model predicts a total Milky Way mass of $2.3 \times 10^{11} M_\odot$, which agrees with recent mass estimates obtained from Gaia DR3 rotation curves (Gaia RC) as shown in Jiao et al. (2023). Moreover, the polytropic halo tail proper of the RAR solutions is more compact than traditional NFW profiles, leading to a Keplerian decline of the outer rotation curve as observed (see Fig. 3.1). In summary, with one single fermionic model for the DM distribution of the Milky Way, we obtain a good fit on three different distance scales of the Galaxy: $\sim 10^{-6}$ kpc (central, S-stars), ~ 14 kpc (middle, GD-1), and ~ 30 kpc (boundary, Gaia RC mass estimate). This kind of first principle fermionic

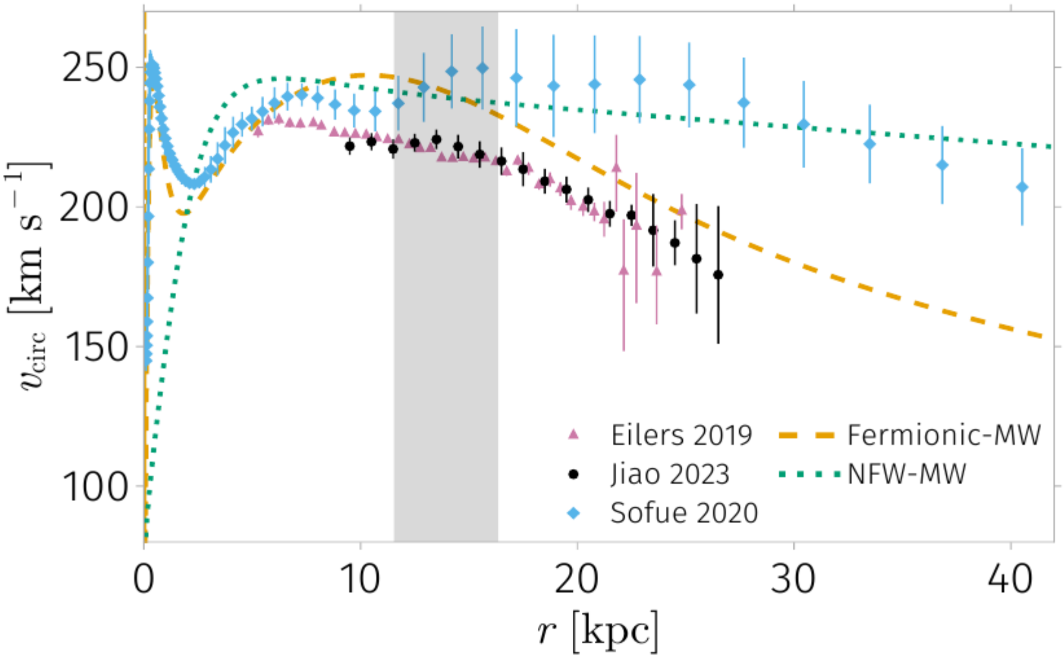

Figure 3.1: Rotation curves of the Fermionic-MW model (in dashed amber) and the NFW-MW model (in dotted green), which fit the GD-1 stream, are compared a posteriori with different observed rotation curves (Eilers et al. 2019 with purple triangles, Sofue 2020 with light blue rhombi, and Jiao et al. 2023 with black circles). Only the Fermionic MW model can account for the GD-1 stream data and the sharp drop of the recent Gaia DR3 rotation curve (Jiao et al., 2023 data). Reproduced from Mestre et al. (2024).

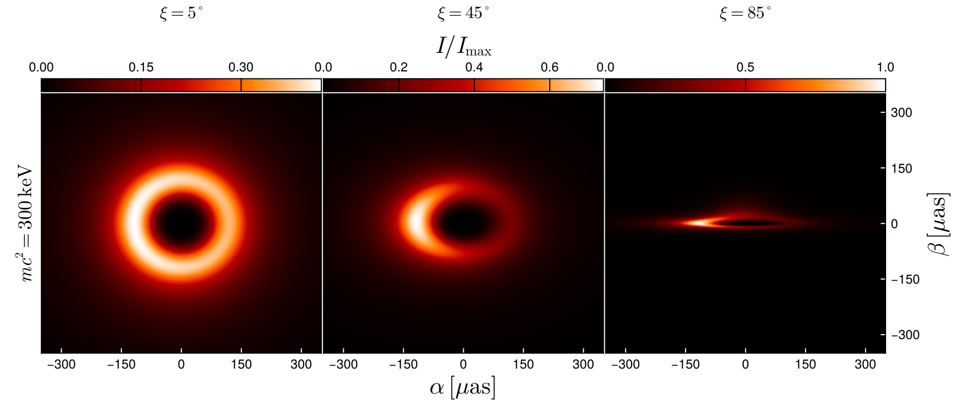

Figure 3.2: Bolometric intensity for an accretion disc with inner radius falling inside the DM core of $M_c \sim 4 \times 10^6 M_\odot$ and particle mass $m = 300$ keV for a Milky Way-like galaxy. The columns correspond to observation inclinations relative to the rotation axis of the disc of $\xi = 5^\circ$, $\xi = 45^\circ$, $\xi = 85^\circ$. The intensity is measured in the static frame. Here, α and β denote the angular coordinates on the sky centered around the radial direction for a fictitious observer at $r = 8.277$ kpc. Reproduced from Pelle et al. (2024).

model is one of a kind, being the only DM halo profile in the literature able to explain observables which constrain the overall gravitational potential of the Galaxy from innermost (i.e. miliparesec) to outermost radial scales.

3.1.2 Imaging a $4 \times 10^6 M_\odot$ fermion core

In Pelle et al. (2024), we moved forward from the traditional analysis of S-cluster stars to analyze the relativistic images as observed by the Event Horizon Telescope at the Galactic center. Indeed, the current images of the supermassive black hole (SMBH) candidates, SgrA* and M87, have opened an unprecedented era for studying strong gravity and the nature of relativistic sources. Very long-baseline interferometry data show images consistent with a central SMBH within General Relativity (GR). However, it is essential to consider whether other well-motivated dark compact objects within GR could produce similar images. As shown previously in the series of papers aimed at the Milky Way, the DM haloes modeled as self-gravitating systems of neutral fermions can harbor very dense fermionic cores at their centers, which can mimic the space-time features of a black hole (BH). Such dense, horizonless DM cores can satisfy the observational constraints: they can be supermassive and compact and lack a hard surface. Thus, in Pelle et al. (2024), we have investigated whether such cores can produce observational signatures similar to those of BHs when illuminated by an accretion disc. We have computed images and spectra of the fermion cores with a general relativistic ray tracing technique, assuming the radiation originates from standard α discs, which are self-consistently solved within the current DM framework.

Our simulated images possess a central brightness depression surrounded by a ring-like feature, resembling what is expected in the BH scenario. For Milky Way-like haloes, central brightness depressions have diameters that go from $\sim 100\,\mu$as (for ~ 300 keV/c^2) down to $\sim 35\,\mu$as (for $m \sim 370$ keV/c^2) as measured from a distance of approximately 8 kpc (see Fig. 8 for an example). Finally, we have shown that the DM cores do not possess photon rings, a key difference from the BH paradigm, which could help discriminate between the models.

3.2 Supermassive black holes: its nature and formation channels

How SMBHs form and grow at high cosmological redshifts has remained elusive for years. The relevance of getting a satisfactory answer exponentially increases with the advent of the new, deep observations of the universe by the JWST at high cosmological redshifts, for example $z \gtrsim 10$. In traditional scenarios, the BHs in the high-z universe should form from the gravitational collapse of hypothetical population III massive stars or gaseous configurations. In the most extreme assumptions, the BHs in these channels do not reach more than a hundred solar masses in the former and a hundred thousand in the latter mechanism. The further growth of the BH requires the accretion of ordinary matter from the galactic environment and the occurrence of galaxy mergers. However, these BH seeds are either too light or the environmental conditions too rare to satisfactorily explain the SMBH population at the centers of the farthest quasars, as observed by JWST, thus challenging our current cosmological understanding.

3.2.1 A new channel for SMBH formation

In a previous article published in 2023 in the Monthly Notices of the Royal Astronomical Society journal Argüelles et al. (2023b), our research team had shown that the gravitational collapse of dense cores of dark matter made of fermions would form SMBHs of tens to hundreds of million solar masses if the neutral (spin 1/2) fermion has a mass in the range of 50 to 100 keV, i.e. between one-tenth and one-fifth of the electron's mass. In that article, the authors showed that these SMBH seeds could comfortably grow by accretion up to a billion solar masses in timescales of a hundred million years. Therefore, this scenario could solve the SMBH formation problem in the high-z universe, providing one can answer the following crucial questions: how does an initially stable dark matter core reach gravitational collapse conditions, how long could that process take, and are those conditions realized in the required moment of the cosmological evolution?

In Argüelles et al. (2024) the authors answered these questions using the fact that galaxy halos are not only made of dark matter but also ordinary (baryonic) matter. The baryonic matter infall and sedimentation in the dark matter core could trigger its gravitational collapse for a threshold amount of baryons that instabilizes the core since baryons provide mass but little pressure (see Fig. 3.3). The publication shows, for example, that a dark matter core that has gained about 35% of its final budget in baryonic matter collapses, forming SMBHs of about a hundred million solar masses. This amount of baryonic matter could be gained in a hundred million-year timescale from a baryonic environment of one solar mass per cubic centimeter of density and a hundred kilometers per second of velocity. See the Fig. 3.4 for details. These values are typically found in cosmological hydrodynamical simulations of high-z halos and observed in the central regions of distant galaxies. The new publication focuses on the viability of the baryon-induced collapse mechanism in three cases: the SMBH formation in the Seyfert galaxy TXS 2116–077 merging with a nearby galaxy, the farthest quasar ever observed, located at $z = 10.3$ at the center of the JWST-galaxy UHZ1, and the so-called little red dots, the population of JWST-SMBHs at $z \approx 4$–6.

Interestingly, the required fermionic cores playing the role of BH seeds are those of the dense core-diluted halo dark matter configurations predicted by the extended RAR model. A series of previous publications (see Argüelles et al. (2023a) for a review) have shown the reliability of such a dark matter candidate as its core-halo dark matter galactic configurations explain a

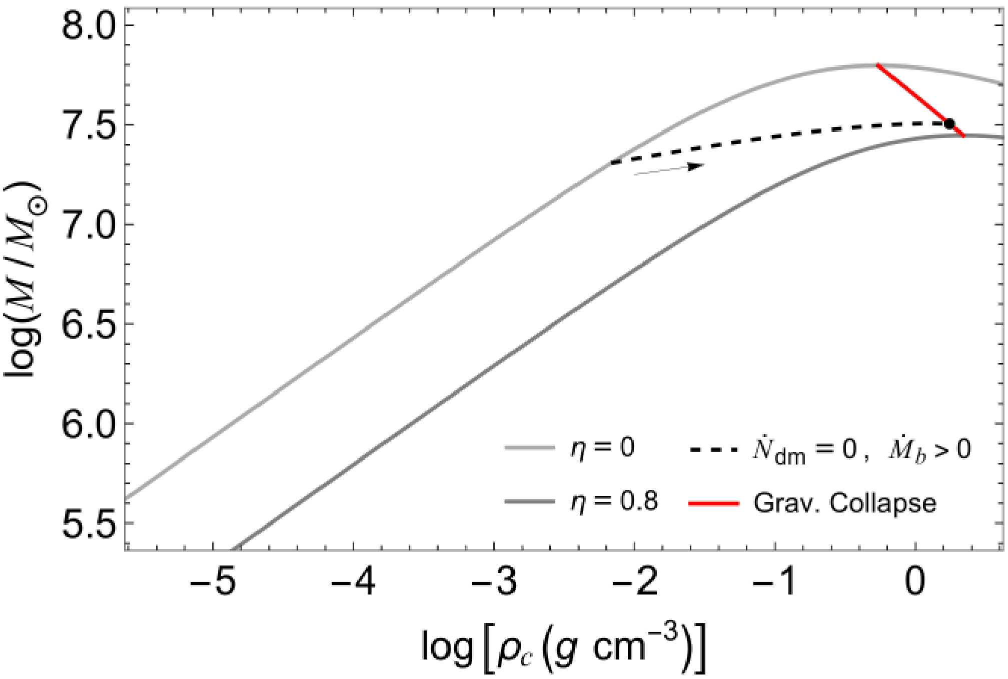

Figure 3.3: Dark matter+baryonic equilibrium configurations for $m = 100$ keV/c^2. The black dashed curve shows the equilibrium configurations at a constant total fermion number. The lighter and darker gray curves are the equilibrium sequences with 0% baryons in the core (i.e. only DM) and 80% baryons respectively. The red curve is the secular instability limit for gravitational collapse. The black-dashed sequence starts with a pure dark matter core of $M_{dm} = 2.03 \times 10^7 M_\odot$ and radius $R_c = 6.67 \times 10^{-5}$ pc. As baryons sink in the core, the configuration follows the black-dashed sequence to the right (see the arrow) until it reaches the critical mass for gravitational collapse (black dot). The critical configuration has a baryon-to-dark-matter mass ratio $\chi_{BH} \approx 0.56$, so baryons contribute 36% and the dark matter 64% to the critical mass, $M_{BH} \approx 3.19 \times 10^7 M_\odot$, i.e., $M_{dm,crit} = 2.04 \times 10^7 M_\odot$ and $M_{b,crit} \approx 1.15 \times 10^7 M_\odot$. Reproduced from Argüelles et al. (2024).

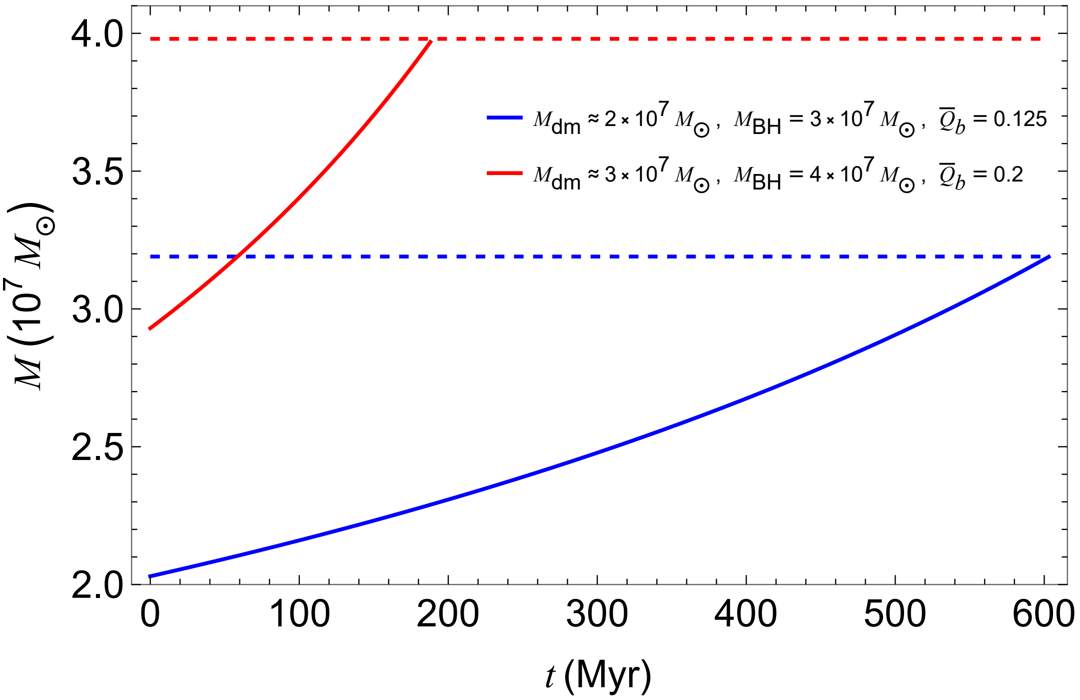

Figure 3.4: Time evolution of the dark matter core mass while accreting baryonic matter (at sub-Eddington rates) for two examples. The blue curve is the evolution of the dark matter core which started accreting with an initial (sub-critical) DM core of mass and central density as shown in Fig. 3.3. The dashed lines indicate the SMBH mass formed. Reproduced from Argüelles et al. (2024).

variety of observables, including the galactic rotation curves, observational universal relations of galaxies, and the motion of the innermost stars near the Milky Way's center, Sgr A* .

3.2.2 The nature of the central engine in low-luminosity AGNs

In Millauro et al. (2024) the attention was centered on fermionic *core-halo* profiles applied to typical active-like galaxies, together with their central accretion processes. The aim was to study the accretion flow and associated emission using generalised α-discs onto horizonless dark compact objects made of semi-degenerate fermions, in order to compare with the traditional BH scenario. An exploration of the free parameters of the RAR profiles (including particle mass) was made for solutions whose central core did not reach the critical mass for collapse, and thus represents an alternative to the traditional BH scenario. This choice is motivated by the ambitious endeavour of trying to understand the very nature of the massive compact objects at galaxy centres, their formation channel, surrounding emission, and finally their relation with the host galaxy and AGN phenomenology.

In analogy to different works using boson stars in the last two decades (Schunck and Mielke, 1999; Torres et al., 2000; Guzmán, 2006; Vincent et al., 2016; Olivares et al., 2020), the objective in Millauro et al. (2024) was to start a research program for AGN phenomenology dedicated to the RAR mode and in particular to the DM fermion-cores at the center of galaxies. The efforts in Millauro et al. (2024) started with the calculation of accretion and corresponding luminosity of barionic matter onto supermassive compact cores made of fermionic DM. This was done by first extending the standard disc model of Shakura & Sunyaev (Shakura and Sunyaev, 1973) in presence of a fermionic DM distribution, using a Keplerian disc and a classical treatment. In the case of fermionic particles, the main motivation comes via the numerous efforts made in the last decade to shed light on the nature of such supermassive dark compact objects and the surrounding DM halo in a unified description (Argüelles et al., 2023a).

The main results found include: i) it always exist a given core compacity -i.e. corresponding particle mass- which produces a luminosity spectrum which is basically indistinguishable from that of a Schwarzschild BH of the same mass as the DM core (see Fig. 3.5); (ii) the disc can enter deep inside the non-rotating DM core, allowing for accretion powered efficiencies as high as 28%, thus comparable to that of a highly rotating Kerr BH. These results, together with the existence of a critical DM core mass of collapse into a supermassive BH, open new avenues of research for two seemingly unrelated topics such as AGN phenomenology and dark matter physics.

Finally, motivated by the Event Horizon Telescope (EHT) observations of the relativistic images in both M87 and the Milky Way, we investigated in Pelle et al. (2024) whether the above fermion-cores in lo luminosity AGNs can produce similar observational signatures to those of BHs when illuminated by an accretion disk. We compute images and spectra of such fermion cores with a general-relativistic ray tracing technique, assuming the radiation originates from standard α disks, which are self-consistently solved within

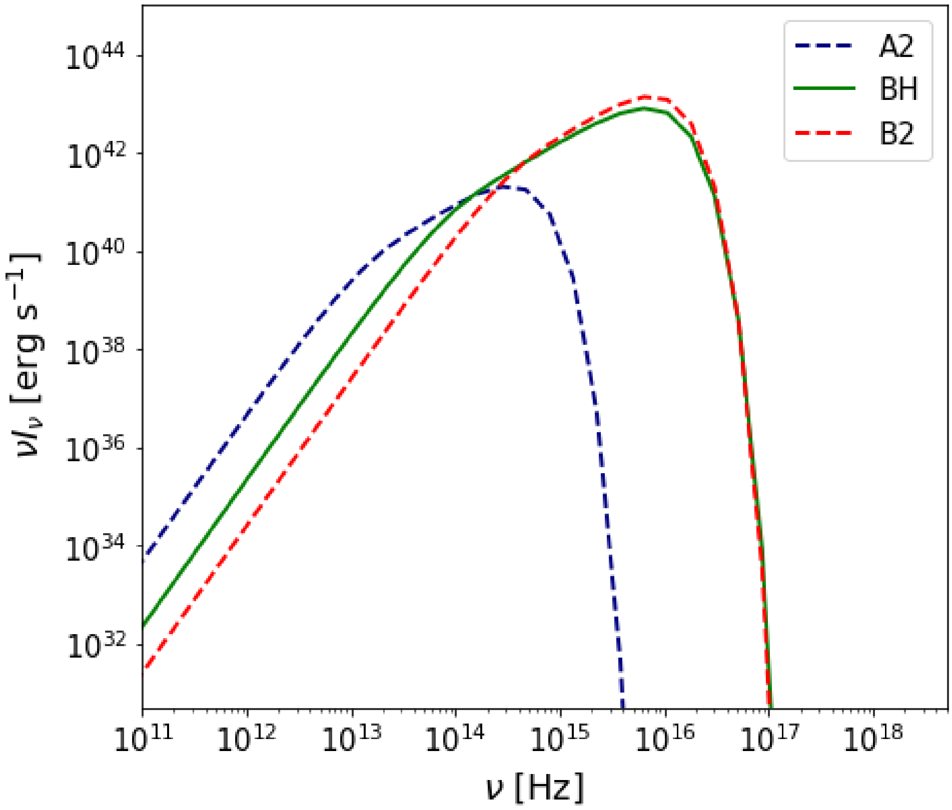

Figure 3.5: Comparison of luminosity for the A2 RAR model ($m = 48$ keV/c^2), B2 RAR model ($m = 200$ keV/c^2) and a BH, all with a mass of $\sim 10^7 M_\odot$. Thus it exist a specific core compacity (i.e. the B2 model) which produces a luminosity spectrum which is basically indistinguishable from that of a BH of the same mass as the DM core. Reproduced from Millauro et al. (2024).

the current DM framework as summarized above. Our simulated images possess a central brightness depression surrounded by a ring-like feature, resembling what is expected in the BH scenario (see Fig. 3.6). Thus the results published this year by our team and collaborators in both Pelle et al. (2024) and Millauro et al. (2024) open promising applications to the problem of the nature of the red-dots as observed by the JWST telescope (see e.g. Matthee et al. (2024)), in terms of DM fermion-cores and its eventual collapse towards a BH.

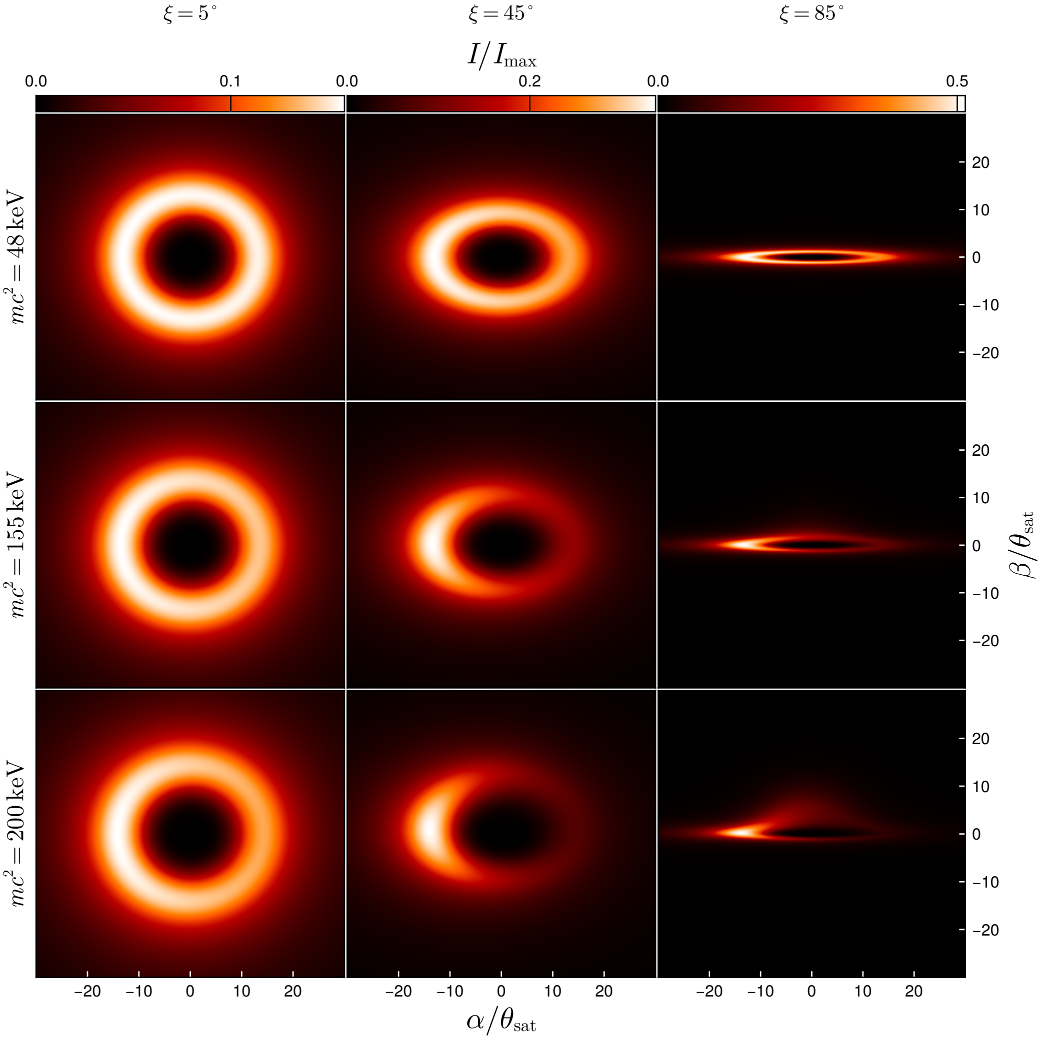

Figure 3.6: Bolometric intensity for an accretion disk around a DM core of $M_{BH} = 1 \times 10^7 M_\odot$ corresponding to low-luminosity AGNs. The central brightness depression surrounded by a ring-like feature, resembles what is expected in the BH scenario for the 200 keV case. The columns correspond to observation inclinations relative to the rotation axis of the disk of $\xi = 5^\circ, 45^\circ, 85^\circ$. Here, α and β denote the angular coordinates on the sky centered around the radial direction, and $\theta_{\mathrm{sat}} = r_{\mathrm{sat}}/r$, i.e., the normalized angular radius. The intensity has been scaled to $I_{\max} = 1.8 \times 10^{16}\,\mathrm{erg\,cm^{-2}\,sr^{-1}\,s^{-1}}$. Reproduced from Pelle et al. (2024).

4 Publications 2024

1. Mestre M. F.; Argüelles C. R.; Carpintero D.; Crespi V.; Krut A., "Modelling the track of the GD-1 stellar stream inside a host with a fermionic dark matter core-halo distribution ", Astronomy & Astrophysics (2024), Volume 689, id. A194, 11 pp.

   Context. Traditional studies of stellar streams typically involve phenomenological ΛCDM halos or ad hoc dark matter (DM) profiles with different degrees of triaxiality, which preclude us from gaining insights into the nature and mass of the DM particles. Recently, the maximum entropy principle of halo formation has been applied to provide a DM halo model that incorporates the fermionic (quantum) nature of the particles while leading to DM profiles that depend on the fermion mass. These profiles develop a more general "dense core – diluted halo" morphology that can explain the Galactic rotation curve, while the degenerate fermion core can mimic the central massive black hole (BH). Aims. We model the GD-1 stellar stream using a spherical core-halo DM distribution for the host that simultaneously explains the dynamics of the S-cluster stars through its degenerate fermion core without a central BH. Methods. We used two optimization algorithms in order to fit both the initial conditions of the stream orbit and the fermionic model. We modeled the baryonic potential with a bulge and two disks (thin and thick) with fixed parameters according to the recent literature. The stream observables were 5D phase-space data from the Gaia DR2 survey. Results. We were able to find good fits for both the GD-1 stream and the S-stars for a family of fermionic core-halo profiles parameterized by the fermion mass. The particle masses are constrained in the range 56 keV c^{-2}, with a corresponding DM core of $\sim 10^3$ Schwarzschild radii, to 360 keV c^{-2}, which corresponds to the most compact core of 5 Schwarzschild radii prior to the gravitational collapse into a BH of about $4 \times 10^6 M_\odot$. Conclusions. This work provides evidence that the fermionic profile is a reliable model for the massive central object and for the DM of the Galaxy. Remarkably, this model predicts a total Milky Way mass of $2.3 \times 10^{11} M_\odot$, which agrees with recent mass estimates obtained from Gaia

DR3 rotation curves (Gaia RC). In summary, with one single fermionic model for the DM distribution of the Milky Way, we obtain a good fit on three totally different distance scales of the Galaxy: $\sim 10^{-6}$ kpc (central, S-stars), $\sim$ 14 kpc (middle, GD-1), and $\sim$ 30 kpc (boundary, Gaia RC mass estimate).

2. Collazo S.; Argüelles C. R.; Mestre M. F.,"La corriente estelar de Sagitario inmersa en un halo de materia oscura fermiónica "Boletín de la Asociación Argentina de Astronomía (2024), vol. 65, p.228-231.

   Under the assumption that dark matter is a neutral fermionic particle distributed on galactic scales according to the Ruffini-Argüelles-Rueda (RAR) model, it was evaluated whether a first principle physics model of this kind is capable of reproducing the 6D observations of the stellar stream of Sagittarius orbiting the Milky Way. The prediction of this stellar stream (i.e. leading arm, trailing arm and main body) was carried out using a spray algorithm, within which the baryonic and dark mass components of the host and progenitor were defined. Under a scenario like this, it is demonstrated that such a spherically symmetric fermionic-halo model is capable of reproducing the main features of the stream.

3. Pelle J.; Argüelles, C. R.; Vieyro F. L.; Crespi V.; Millauro C.; Mestre M. F.; Reula O.; Carrasco F., "Imaging fermionic dark matter cores at the centre of galaxies ", Monthly Notices of the Royal Astronomical Society (2024), Volume 534, Issue 2, pp.1217-1226.

   Current images of the supermassive black hole (SMBH) candidates at the centre of our Galaxy and M87 have opened an unprecedented era for studying strong gravity and the nature of relativistic sources. Very-long-baseline interferometry data show images consistent with a central SMBH within General Relativity (GR). However, it is essential to consider whether other well-motivated dark compact objects within GR could produce similar images. Recent studies have shown that dark matter (DM) haloes modelled as self-gravitating systems of neutral fermions can harbour very dense fermionic cores at their centres, which can mimic the space-time features of a black hole (BH). Such dense, horizonless DM cores can satisfy the observational constraints: they can be supermassive and compact and lack a hard surface. We investigate whether such cores can produce similar observational signatures to those of BHs when illuminated by an accretion disc. We compute images and spectra of the fermion cores with a general-relativistic ray tracing technique, assuming the radiation originates from standard α discs, which are self-consistently solved within the current DM framework. Our simulated images possess a central brightness depression surrounded by a ring-like feature, resembling what is expected in the BH scenario. For Milky Way-like haloes, the central brightness depressions have diameters down to $\sim 35\,\mu$as as measured from a distance of approximately 8 kpc. Finally, we show that the DM cores do not possess photon rings, a key difference from the BH paradigm, which could help discriminate between the models.

4. Millauro C.; Argüelles, C. R.; Vieyro F. L.; Crespi V.; Mestre M. F., "Accretion discs onto supermassive compact objects: A portal to dark matter physics in active galaxies ", Astronomy & Astrophysics, Volume 685, id.A24, 11 pp.

   Context. The study of the physics of the accretion discs that develop around supermassive black hole (BH) candidates provides essential theoretical tools to test their nature. Aims: Here, we study the accretion flow and associated emission using generalised α-discs accreting onto horizonless dark compact objects in order to make comparisons with the traditional BH scenario. The BH alternative proposed here consists in a dense and highly degenerate core made of fermionic dark matter (DM) and surrounded by a more diluted DM halo. This dense core-diluted halo DM configuration is a solution of Einstein's equation of general relativity (GR) in spherical symmetry, which naturally arises once the quantum nature of the DM fermions is duly accounted for. Methods: The methodology followed in this work consists in first generalising the theory of α-discs to work in the presence of regular and horizonless compact objects, and then applying it to the case of core-halo DM profiles typical of active-like galaxies. Results: The fact that the compactness of the dense and transparent DM core scales with particle mass allows the following key findings of this work: (i) There is always a given core compacity - corresponding particle mass - that produces a luminosity spectrum that is almost indistinguishable from that of a Schwarzschild BH of the same mass as the DM core. (ii) The disc can enter deep inside the non-rotating DM core, allowing accretion-powered efficiencies of as high as 28%, which is comparable to that of a highly rotating Kerr BH. Conclusions: These results, together with the existence of a critical DM core mass of collapse into a supermassive BH, open new avenues of research for two seemingly unrelated topics: AGN phenomenology and dark matter physics.

5. Argüelles, C. R.; Rueda, J. A.; Ruffini, R., "Baryon-induced Collapse of

Dark Matter Cores into Supermassive Black Holes”, The Astrophysical Journal Letters (2024), Volume 961, Issue 1, id.L10, 6 pp.

Non-linear structure formation for fermionic dark matter particles leads to dark matter density profiles with a degenerate compact core surrounded by a diluted halo. For a given fermion mass, the core has a critical mass that collapses into a supermassive black hole (SMBH). Galactic dynamics constraints suggest a ~ 100 keV$/c^2$ fermion, which leads to $\sim 10^7 M_\odot$ critical core mass. Here, we show that baryonic (ordinary) matter accretion drives an initially stable dark matter core to SMBH formation and determine the accreted mass threshold that induces it. Baryonic gas density ρ_b and velocity v_b inferred from cosmological hydro-simulations and observations produce sub-Eddington accretion rates triggering the baryon-induced collapse in less than a Gyr. This process produces active galactic nuclei in galaxy mergers and the high-redshift Universe. For TXS 2116–077, merging with a nearby galaxy, the observed $3 \times 10^7 M_\odot$ SMBH, for $Q_b = \rho_b / v_b^3 = 0.125 M_\odot / (100\text{km/s pc})^3$, forms in ≈ 0.6 Gyr, consistent with the 0.5–2 Gyr merger timescale and younger jet. For the farthest central SMBH detected by the *Chandra* X-ray satellite in the $z = 10.3$ UHZ1 galaxy observed by the James Webb Space Telescope (*JWST*), the mechanism leads to a $4 \times 10^7 M_\odot$ SMBH in 87–187 Myr, starting the accretion at $z = 12$–15. The baryon-induced collapse can also explain the $\approx 10^7$–$10^8 M_\odot$ SMBHs revealed by the JWST at $z \approx 4$–6. After its formation, the SMBH can grow to a few $10^9 M_\odot$ in timescales shorter than a Gyr via sub-Eddington baryonic mass accretion.

Bibliography

ARGÜELLES, C.R., BECERRA-VERGARA, E.A., KRUT, A., YUNIS, R., RUEDA, J.A. AND RUFFINI, R.
≪Reshaping our understanding on structure formation with the quantum nature of the dark matter≫.
International Journal of Modern Physics D, **31(2)**, 2230002 (2022a).

ARGÜELLES, C.R., BECERRA-VERGARA, E.A., RUEDA, J.A. AND RUFFINI, R.
≪Fermionic Dark Matter: Physics, Astrophysics, and Cosmology≫.
Universe, **9(4)**, 197 (2023a).

ARGÜELLES, C.R., BOSHKAYEV, K., KRUT, A., NURBAKHYT, G., RUEDA, J.A., RUFFINI, R., URIBE-SUÁREZ, J.D. AND YUNIS, R.
≪On the growth of supermassive black holes formed from the gravitational collapse of fermionic dark matter cores≫.
Monthly Notices of the Royal Astronomical Society, **523(2)**, pp. 2209–2218 (2023b).

ARGÜELLES, C.R., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪Novel constraints on fermionic dark matter from galactic observables I: The Milky Way≫.
Physics of the Dark Universe, **21**, 82 (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≫.
Physics of the Dark Universe, **24**, 100278 (2019).

ARGÜELLES, C.R., MESTRE, M.F., BECERRA-VERGARA, E.A., CRESPI, V., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪What does lie at the Milky Way centre? Insights from the S2-star orbit precession≫.

Monthly Notices of the Royal Astronomical Society, **511(1)**, pp. L35–L39 (2022b).

ARGÜELLES, C.R., RUEDA, J.A. AND RUFFINI, R.
≪Baryon-induced Collapse of Dark Matter Cores into Supermassive Black Holes≫.
Astrophysical Journal, **961(1)**, L10 (2024).

ARGÜELLES, C.R., DÍAZ, M.I., KRUT, A. AND YUNIS, R.
≪On the formation and stability of fermionic dark matter haloes in a cosmological framework≫.
Monthly Notices of the Royal Astronomical Society, **502(3)**, pp. 4227–4246 (2021).

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 and Astrophysics, **641**, A34 (2020).

BECERRA-VERGARA, E.A., ARGÜELLES, C.R., KRUT, A., RUEDA, J.A. AND RUFFINI, R.
≪Hinting a dark matter nature of Sgr A* via the S-stars≫.
Monthly Notices of the Royal Astronomical Society, **505(1)**, pp. L64–L68 (2021).

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).

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

GUZMÁN, F.S.
≪Accretion disk onto boson stars: A way to supplant black hole candidates≫.
Physical Review D, **73(2)**, 021501 (2006).

JIAO, Y., HAMMER, F., WANG, H., WANG, J., AMRAM, P., CHEMIN, L. AND YANG, Y.
≪Detection of the Keplerian decline in the Milky Way rotation curve≫.
Astronomy & Astrophysics, **678**, A208 (2023).

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

KRUT, A., ARGÜELLES, C.R., CHAVANIS, P.H., RUEDA, J.A. AND RUFFINI, R.
≪Galaxy Rotation Curves and Universal Scaling Relations: Comparison between Phenomenological and Fermionic Dark Matter Profiles≫.
Astrophysical Journal, **945(1)**, 1 (2023).

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

MATTHEE, J., NAIDU, R.P., BRAMMER, G., CHISHOLM, J., EILERS, A.C., GOULDING, A., GREENE, J., KASHINO, D., LABBE, I., LILLY, S.J. ET AL.
≪Little Red Dots: An Abundant Population of Faint Active Galactic Nuclei at z $\sim$ 5 Revealed by the EIGER and FRESCO JWST Surveys≫.
Astrophysical Journal, **963(2)**, 129 (2024).

MESTRE, M.F., ARGÜELLES, C.R., CARPINTERO, D.D., CRESPI, V. AND KRUT, A.
≪Modeling the track of the GD-1 stellar stream inside a host with a fermionic dark matter core-halo distribution≫.
Astronomy & Astrophysics, **689**, A194 (2024).

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).

MILLAURO, C., ARGÜELLES, C.R., VIEYRO, F.L., CRESPI, V. AND MESTRE, M.F.
≪Accretion discs onto supermassive compact objects: A portal to dark matter physics in active galaxies≫.
Astronomy & Astrophysics, **685**, A24 (2024).

Olivares, H., Younsi, Z., Fromm, C.M., De Laurentis, M., Porth, O., Mizuno, Y., Falcke, H., Kramer, M. and Rezzolla, L.
≪How to tell an accreting boson star from a black hole≫.
Monthly Notices of the Royal Astronomical Society, **497(1)**, pp. 521–535 (2020).

Pelle, J., Argüelles, C.R., Vieyro, F.L., Crespi, V., Millauro, C., Mestre, M.F., Reula, O. and Carrasco, F.
≪Imaging fermionic dark matter cores at the centre of galaxies≫.
Monthly Notices of the Royal Astronomical Society, **534(2)**, pp. 1217–1226 (2024).

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).

Schunck, F.E. and Mielke, E.W.
≪Boson Stars: Rotation, Formation, and Evolution≫.
GR and Gravitation, **31**, p. 787 (1999).

Shakura, N.I. and Sunyaev, R.A.
≪Black holes in binary systems. Observational appearance.≫
Astronomy & Astrophysics, **24**, pp. 337–355 (1973).

Torres, D.F., Capozziello, S. and Lambiase, G.
≪Supermassive boson star at the galactic center?≫
Physical Review D, **62(10)**, 104012 (2000).

Vincent, F.H., Meliani, Z., Grandclément, P., Gourgoulhon, E. and Straub, O.
≪Imaging a boson star at the Galactic center≫.
Classical and Quantum Gravity, **33(10)**, 105015 (2016).