Quantum warm dark matter fermions and gravitation determine the observed galaxy structures

Dark matter (DM) is the main component of galaxies. Quantum mechanics is a cornerstone of physics from microscopic to macroscopic systems as quantum liquids He^3, white dwarf stars and neutron stars. A study by a team of CNRS scientists from Paris Observatory, Pierre et Marie Curie University, and INFN-Milano Bicocca, suggests for the first time that quantum mechanics is also responsible of galaxy structures at the kpc scales and below: near the galaxy center, below $10-100$ pc, the DM *quantum* effects are important for warm DM (WDM), that is for DM particles with masses in the keV scale. A new approach to galaxy structure and a set of results follow in remarkable agreement with observations: (i) Dwarf galaxies turn to be quantum macroscopic objects for WDM supported against gravity by the WDM fermion pressure. (ii) A theoretical *analytic* framework from atomic physics is implemented to determine galaxy structure from the most compact dwarf galaxies to the largest dilute galaxies (spirals, ellipticals). The obtained galaxy mass, halo radius, phase-space density, velocity dispersion, are fully consistent with observations. (iii) Interestingly enough, a *minimal* mass and *minimal* velocity dispersion are found for DM dominated objects, which in turn imply an universal minimal mass $m_{min} = 1.9$ keV for the WDM particle.

Dark matter (DM) is the main component of galaxies, especially of dwarf galaxies. Cold DM (CDM) is formed by very heavy particles, which are very slow (almost zero velocity), and produce a huge overabundance of small structures, substructures or "satellites" below ~ 50 kpc till very small scales ~ 0.005 pc. This constitutes, as is well known, one of the most serious drawbacks for CDM (also known as the "CDM satellites problem") . On the contrary, Warm DM (WDM) is formed by particles with masses in the intermediate scales, the keV scale, which have high enough velocities and produce DM structures in the range of scales $\lesssim 50$ kpc in agreement with observations: In WDM structure formation, substructures below the scale ~ 50 kpc are naturally not formed. For all scales larger than 50 kpc, WDM yields the same results than CDM and agrees with the galactic as well as cosmological observations: small as well as large scale structure observations and CMB anisotropies.

Astronomical observations show that the DM galaxy density profiles are cored, that is, profiles which are flat at the center. On the contrary, N-body CDM simulations exhibit cusped density profiles, with a typical $1/r$ cusped behaviour near the galaxy center $r = 0$. Classical N-body WDM simulations exhibit cores but with sizes much smaller than the observed cores. A new approach to this problem has been recently developped by the team thanks to quantum mechanics.

A direct way to see whether a system formed by particles has a classical or quantum nature is to compare the particle de Broglie wavelength $\lambda_{dB} = \hbar/(m\ \sigma)$, with the inter-particle distance d. The ratio of the two lengths can be expressed as

$$\mathcal{R} \equiv \frac{\lambda_{dB}}{d} = \hbar \left(\frac{Q_h}{m^4}\right)^{\frac{1}{3}} \qquad , \qquad Q_h \equiv \frac{\rho_h}{\sigma^3} \ .$$

where Q_h is the DM phase space density, ρ_h and σ being the halo density and the velocity dispersion, respectively. Values of $\mathcal{R}$ much smaller than unity correspond to classical and semiclassical (semiquantum) physics while $\mathcal{R} \sim 1$ or larger corresponds to the extreme quantum regime. The observed values of Q_h in Table I listed from the more small compact objects and dwarfs compact galaxies till the largest galaxies yield $\mathcal{R}$ in the range

$$2 \times 10^{-3} < \mathcal{R}\ (m/\mathrm{keV})^{\frac{4}{3}} < 1.4 \ .$$

The larger values of $\mathcal{R}$ are for the ultracompact objects and dwarf galaxies, the smaller values of $\mathcal{R}$ are for large spirals. The values of $\mathcal{R}$ around unity clearly imply from the observations that compact objects and dwarf galaxies are natural *macroscopic quantum objects* for WDM.

Fermions always provide a non vanishing pressure of quantum nature due to the combined action of the Pauli exclusion principle and Heisenberg uncertainty principle. Quantum effects for WDM fermions rule out the presence of galaxy cusps for WDM and enlarge the classical core sizes because their *repulsive and non-local* nature extend well beyond the small *pc* scales. Smoothing the density profile at the central regions has an effect on the whole galaxy halo.

Galaxy	$\frac{r_h}{\text{pc}}$	$\frac{\sigma}{\frac{\text{km}}{\text{s}}}$	$\frac{\hbar^{\frac{3}{2}}\sqrt{Q_h}}{(\text{keV})^2}$	$\rho(0)/\frac{M_\odot}{(\text{pc})^3}$	$\frac{M_h}{10^6\,M_\odot}$
Willman 1	19	4	0.85	6.3	0.029
Segue 1	48	4	1.3	2.5	1.93
Leo IV	400	3.3	0.2	.19	200
Canis Venatici II	245	4.6	0.2	0.49	4.8
Coma-Berenices	123	4.6	0.42	2.09	0.14
Leo II	320	6.6	0.093	0.34	36.6
Leo T	170	7.8	0.12	0.79	12.9
Hercules	387	5.1	0.078	0.1	25.1
Carina	424	6.4	0.075	0.15	32.2
Ursa Major I	504	7.6	0.066	0.25	33.2
Draco	305	10.1	0.06	0.5	26.5
Leo I	518	9	0.048	0.22	96
Sculptor	480	9	0.05	0.25	78.8
Boötes I	362	9	0.058	0.38	43.2
Canis Venatici I	1220	7.6	0.037	0.08	344
Sextans	1290	7.1	0.021	0.02	116
Ursa Minor	750	11.5	0.028	0.16	193
Fornax	1730	10.7	0.016	0.053	1750
NGC 185	450	31	0.033	4.09	975
NGC 855	1063	58	0.01	2.64	8340
Small Spiral	5100	40.7	0.0018	0.029	6900
NGC 4478	1890	147	0.003	3.7	6.55×10^4
Medium Spiral	1.9×10^4	76.2	3.7×10^{-4}	0.0076	1.01×10^5
NGC 731	6160	163	9.27×10^{-4}	0.47	2.87×10^5
NGC 3853	5220	198	8.8×10^{-4}	0.77	2.87×10^5
NGC 499	7700	274	5.9×10^{-4}	0.91	1.09×10^6
Large Spiral	5.9×10^4	125	0.96×10^{-4}	2.3×10^{-3}	$1. \times 10^6$

TABLE I: Observed values r_h, σ, $\sqrt{Q_h}$, $\rho(0)$ and M_h covering from ultracompact objects and dwarf galaxies to large spiral galaxies. The phase space density is larger for smaller galaxies, both in mass and size. The phase space density is obtained from the stars velocity dispersion which is expected to be smaller than the DM velocity dispersion. Therefore, the reported Q_h are in fact upper bounds to the true values.

The team developped a physical *analytic* framework to the galaxy structures which accounts for the quantum nature of the WDM fermions and determines selfconsistently the gravitational potential and the *galaxy equation of state.* The *full range* of physical galaxy situations is covered: from the compact dwarfs (in the extreme quantum degenerate fermions limit) till the large galaxies, spiral and ellipticals (in the dilute classical and semiclassical regime), passing by all the intermediate galaxy masses and sizes. In this framework, some results obtained by the team are the following:

- A one parameter family of galaxy solutions parametrized by the value of the chemical potential at the origin $\nu(0)$ or equivalently, by the phase-space density at the origin $Q(0)$: Large positive values of $\nu(0)$, or $Q(0)$, correspond to the most compact galaxies while large negative values of $\nu(0)$ yield dilute objects (intermediate and large galaxies, spiral and ellipticals). Approaching the dilute regime yields larger and larger halo radii, galaxy masses and velocity dispersions. Their maximum values are limited by the initial conditions provided by the primordial power spectrum. The theoretical values for the core radius r_h, core galaxy mass M_h and velocity dispersion $\sigma(0)$ vary very little with the specific form of the phase-space distribution function (equilibrium or out of equilibrium distributions give similar results).

- All obtained density profiles are cored. The core sizes r_h are in agreement with the observations, from the compact galaxies where $r_h \sim 20$ pc till the spiral and elliptical galaxies where $r_h \sim 0.2 - 60$ kpc. The larger and

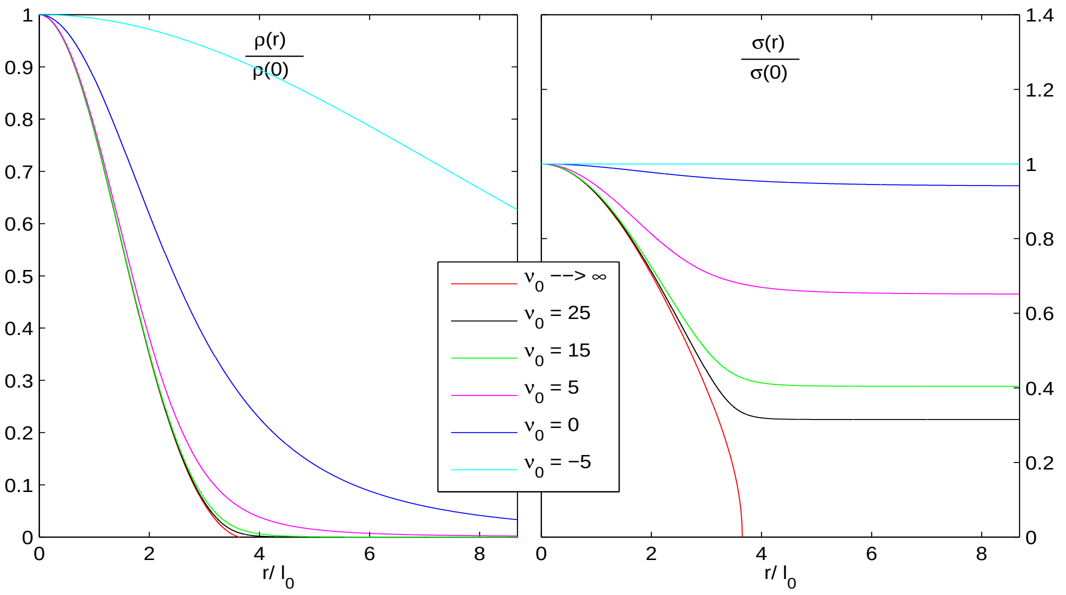

FIG. 1: The obtained density and velocity profiles, $\rho(r)/\rho_0$ and $\sigma(r)/\sigma(0)$, for different values of the chemical potential at the origin ν_0. Large positive values of ν_0 correspond to compact galaxies, while negative values of ν_0 correspond to the classical regime describing spiral and elliptical galaxies. All density profiles are cored. The sizes of the cores r_h are in agreement with the observations, from the compact galaxies where $r_h \sim 35$ pc till the spiral and elliptical galaxies where $r_h \sim .2 - 60$ kpc. The larger and positive is ν_0, the smaller is the core. The minimal one arises in the degenerate case $\nu_0 \to +\infty$ (compact dwarf galaxies).

positive is the chemical potential $\nu(0)$, the smaller is the core. The minimal one arises in the degenerate case $\nu(0) \to +\infty$ (compact dwarf galaxies). Fig. 1 displays the theoretically obtained density and velocity profiles.

The left panel of fig. 2 shows the obtained (dimensionless) phase-space density $\hbar^3 \; Q(0)/(\text{keV})^4$. The observed values are also depicted. The right panel shows the obtained galaxy halo masses. Good agreement is found in **all** the range of galaxies for a DM particle mass m around 2 keV. Error bars of the observational data are not shown but they are at least about $10 - 20\%$.

- A *minimal* galaxy mass and *minimal* velocity dispersion are found. This in turn implies a minimal mass m_{min} for the WDM particle. This minimal WDM mass is a *universal* value, *independent* of the WDM particle physics model because only relies on the degenerate quantum fermion state, which is universal whatever is the non-degenerate regime. These results and the observed halo radius and mass of the compact galaxies also provide further indication that the WDM particle mass m is approximately around 2 keV. More precise data will make this estimation more precise.

To **conclude**, it is highly remarkable that in the context of warm dark matter, the quantum description provided by this semiclassical framework, (quantum WDM and classical gravitation), is able to reproduce such broad variety of galaxies, as shown in Figs 1 and 2. The resulting galaxy halo radius, galaxy masses and velocity dispersion are fully consistent with observations for all different types of galaxies, Figs 1, 2 and Table I . Fermionic WDM treated quantum mechanically, as it must be, is able to reproduce the observed galactic cores and their sizes. In addition, WDM simulations produce the right DM structures in agreement with observations for scales $\gtrsim$ kpc.

Baryons have not yet included in the present study. This is fully justified because on one hand dwarf compact galaxies are composed today 99.99% of DM, and on the other hand the baryon fraction in large galaxies can reach values up to 1 - 3 %. Since Fermionic WDM by itself produces galaxies and structures in agreement with observations for all types of galaxies, masses and sizes, the effect of including baryons is expected to be a small correction to these pure WDM results, consistent with the fact that dark matter is in average six times more abundant than baryons.

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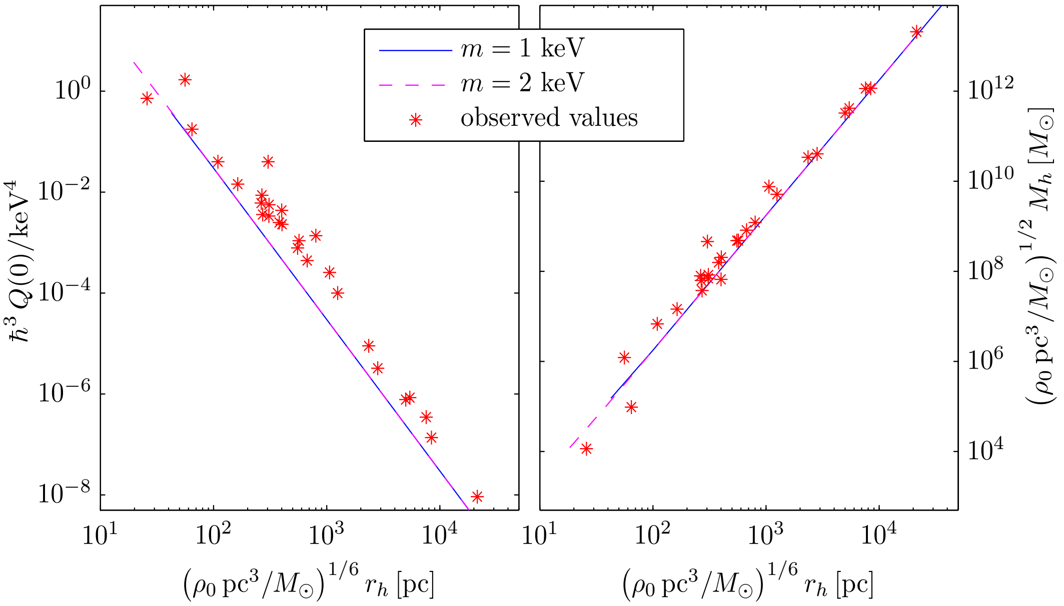

FIG. 2: The left panel displays the (dimensionless) obtained galaxy phase-space density $\hbar^3\ Q(0)/(\mathrm{keV})^4 = (m/\mathrm{keV})^4$ for WDM fermions of mass $m = 1$ and 2 keV versus the ordinary logarithm of the product $\log_{10}\{r_h\ [\mathrm{pc}^3\ \rho_0/M_\odot]^{\frac{1}{6}}\}$ in parsecs. The red stars $*$ are the observed values of $\hbar^3\ Q(0)/(\mathrm{keV})^4$. The observed values Q_h from the stars' velocity dispersion are in fact upper bounds for the DM Q_h and therefore the theoretical curve is slightly below them. The right panel displays the obtained galaxy masses $(M/M_\odot)\sqrt{M_\odot/[\rho_0\ \mathrm{pc}^3]} = 0.82296\ 10^5\ (\mathrm{keV}/m)^4$ for WDM fermions of mass $m = 1$ and 2 keV versus the product $r_h\ [\mathrm{pc}^3\ \rho_0/M_\odot]^{\frac{1}{6}}$ in parsecs. The red stars $*$ are the observed values of $(M/M_\odot)\sqrt{M_\odot/[\rho_0\ \mathrm{pc}^3]}$.

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