Cosmic structure as the quantum interference of a coherent dark wave

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The conventional cold-particle interpretation of dark matter (known as ‘cold dark matter’, or CDM) still lacks laboratory support and struggles with the basic properties of common dwarf galaxies, which have surprisingly uniform central masses and shallow density profiles.⁵⁻⁹ In contrast, galaxies predicted by CDM extend to much lower masses, with steeper, singular profiles.¹⁰ This tension motivates cold, wavelike dark matter (ψDM) composed of a non-relativistic Bose–Einstein condensate, so the uncertainty principle counters gravity below a Jeans scale.¹⁰⁻¹² Here we achieve cosmological simulations of this quantum state at unprecedentedly high resolution capable of resolving dwarf galaxies, with only one free parameter, mₜ, the boson mass. We demonstrate the large-scale structure is indistinguishable from CDM, as desired, but differs radically inside galaxies where quantum interference forms solitonic cores surrounded by extended haloes of fluctuating density granules. These results allow us to determine mₜ = (8.0⁺³.3₋².2) x 10⁻²³ eV using stellar phase-space distributions in dwarf spheroidal galaxies. Denser, more massive solitons are predicted for Milky Way sized galaxies, providing a substantial seed to help explain early spherical formation. The onset of galaxy formation is substantially delayed relative to CDM, appearing at redshift z < 13 in our simulations.

Standard, thermally generated dark matter remains firmly undetected in laboratory searches for weakly interacting massive particles (WIMPs; ref. 13). Non-thermal bosonic fields, particularly scalar fields, provide another well-motivated class of dark matter, formed in a non-relativistic, low-momentum state as a cold Bose–Einstein condensate (BEC), and increasingly motivated by extensions of the Standard Model of particle physics and to the mechanism driving the universal expansion.¹⁴ The field in this context can be described by a coherent wave function \( \psi \) with an interference pattern determining the distribution of dark matter, which we term ψDM. Axions are long-standing CDM candidates of this form, and higher-dimensional theories motivate an ‘axiverse’, where a discrete mass spectrum of axion-like particles spans many decades, possibly affecting cosmic structure.¹⁵

The distribution of ψDM mimics particle CDM on large scales,¹⁶⁻¹⁷, and hence distinguishing between CDM and cold, wavelike ψDM is best made on small scales owing to the additional quantum stress.¹⁰⁻¹²,¹⁷ Dwarf spheroidal (dSph) galaxies are the smallest and most common class of galaxy with internal motions dominated by dark matter. Their basic properties are very hard to explain with standard CDM, including the surprising uniformity of their central masses, \( M < 300 \) pc \( \approx 10^⁷ M_\odot \), where \( M_\odot \) is the solar mass, and shallow density profiles.¹⁻⁵ In contrast, galaxies predicted by CDM extend to much lower masses, well below the observed dwarf galaxies, with steeper, singular mass profiles.⁶⁻⁹ Adjustments to standard CDM addressing these difficulties consider particle collisions,¹⁸, or warm dark matter (WDM; ref. 19). WDM can be tuned to suppress small-scale structures, but does not provide large enough flat cores.²⁰ Collisions CDM can be adjusted to generate flat cores, but cannot suppress low-mass galaxies without resorting to other baryonic physics.²¹ Better agreement is expected for ψDM because the uncertainty principle counters gravity below a Jeans scale, simultaneously suppressing small-scale structures and limiting the central density of collapsed haloes.¹⁰⁻¹²

Detailed examination of structure formation with ψDM is therefore highly desirable, but, unlike the extensive N-body investigation of standard CDM, no sufficiently high resolution simulations of ψDM have been attempted. The wave mechanics of ψDM can be described by Schrödinger’s equation, coupled to gravity by means of Poisson’s equation with negligible microscopic self-interaction. The dynamics here differs from collisionless particle CDM by a new form of stress tensor from quantum uncertainty,

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The central density profiles of all our collapsed cores fit well the stable soliton solution of the Schrödinger–Poisson equation, as shown in Fig. 3 (see also Supplementary Section 2 and Figs 2 and 4). On the other hand, except for the lightest halo, which has just formed and is not yet virialized, the outer profiles of other haloes possess a steepening logarithmic slope, similar to the Navarro–Frenk–White (NFW) profile\textsuperscript{23} of standard CDM. These solitonic cores, which are gravitationally self-bound and appear as additional mass clumps superposed on the NFW profile, are clearly distinct from the cores formed by WDM and collisional CDM, which truncate the NFW cuspy inner profile at lower values and require an external halo for confinement. The radius of the soliton scales inversely with mass, such that the widest cores are the least massive and are hosted by the least massive galaxies. Eighty percent of the haloes in the simulation have $M_{\text{vir}} \sim 10^8$–$10^{10} M_\odot$, but exist only briefly as they are vulnerable to tidal disruption by large galaxies in our simulations. Together with the cutoff in the power spectrum at the Jeans scale (Supplementary Fig. 3), this leads to a marked suppression of substructure below a few times $10^8 M_\odot$ relative to the prediction of standard CDM (refs 8,9). A quantitative evaluation of the mass function of satellite galaxies predicted by CDM with larger simulations is thus another crucial test to be addressed.

The prominent solitonic cores uncovered in our simulations provide an opportunity to estimate the boson mass, $m_B$, by comparison with observations, particularly for dSph galaxies where dark matter dominates. The local Fornax dSph galaxy is the best studied case, with thousands of stellar velocity measurements, allowing a detailed comparison with our soliton mass profile. We perform a Jeans analysis for the dominant intermediate metallicity stellar population, which exhibits a nearly uniform projected velocity dispersion ($\sigma_z$; ref. 25). We simultaneously...
reproduce well the radial distribution of the stars\(^{25}\) (Fig. 4a) and their velocity dispersion with negligible velocity anisotropy, with \(m_\alpha = (8.0^{+1.0}_{-1.0}) \times 10^{-25}\) eV and a core radius \(r_\alpha = 0.93^{+0.14}_{-0.12}\) kpc (Supplementary Fig. 5). The corresponding core mass \(M(r \leq r_\alpha)\) is \(9.2 \times 10^5\ M_\odot\), which is hosted by a halo with virial mass \(\approx 4 \times 10^8\ M_\odot\) in the simulations. These results are similar to other estimates for Fornax\(^{26,27}\) (Fig. 4b) and consistent with other dSph galaxies derived by a variety of means\(^{26,28}\) (see Supplementary Section 3 for details).

For more massive galaxies, the solitons we predict are denser and more massive, scaling approximately as \(M_c \propto M_{\text{vir}}^{1/3}\). So for the Milky Way, adopting a total mass of \(M_{\text{vir}} = 10^{12}\ M_\odot\), we expect a soliton of \(M_t \approx 2 \times 10^5\ M_\odot\), with a core radius \(\approx 180\) pc and a potential depth corresponding to a line-of-sight velocity dispersion \(\sigma_t \approx 115\) km s\(^{-1}\) for test particles satisfying the virial condition with the soliton potential. At face value this seems consistent with the Milky Way bulge velocity dispersion, where a distinctive flat peak is observed at a level of \(\sigma_t \approx 110\) km s\(^{-1}\) within a projected radius \(\sim 200\) pc (refs 29,30). Such cores clearly have implications for the creation of spheroids, acting as an essential seed for the prompt accretion of gas within a deepened potential. Indeed, bulge stars with [Fe/H] \(\geq -1.0\) are firmly established as a uniformly old population that formed rapidly\(^{31,32}\), a conclusion that standard ΛCDM struggles to explain through extended accretion and merging\(^{35}\). The implications for early spheroid formation and compact nuclear objects in general can be explored self-consistently with the addition of baryons to the ψDM code, to model the interplay among stars, gas and ψDM, which will provide model rotation curves for an important test of this model.

At high redshift, the earliest galaxies formed from ψDM are delayed relative to standard CDM, limited by the small amplitude of the Jeans mass at radiation–matter equality, after which the first structures grow. This is demonstrated with a ψDM simulation of a 30 h\(^{-1}\) Mpc box where we adopt \(m_\alpha = 8.0 \times 10^{-23}\) eV derived above. The first bound object collapses at \(z \approx 13\), with a clear solitonic core of mass \(\sim 10^7\ M_\odot\) and radius \(\sim 300\) pc, whereas under ΛCDM the first objects should form at \(z \approx 50\) with masses of only \(10^8\)–\(10^9\ M_\odot\) (ref. 32). The highest redshift galaxy at present at \(z \approx 10.7\) is multiply lensed, seeming smooth and spherical, with a stellar radius \(\sim 100\) pc (ref. 33), similar to local dSph galaxies. Deeper cluster lensing data from the Hubble ‘Frontier Fields’ programme will soon meaningfully explore the mass limits of galaxy formation to higher redshift, allowing us to better distinguish between particle and wavellite cold dark matter.

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Author contributions

Each author has contributed significantly to this paper. In particular, T.C. conceived and supervised the project, H-Y.S. developed the code and conducted the simulations, the results of which have been linked by T.B. to the observations.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.C.

Competing financial interests

The authors declare no competing financial interests.