PROCEEDINGS OF SCIENCE

The Dark Matter Mystery for Poets

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A data driven solution to the Dark Matter Mystery is presented. This version of my talk is intended for “poets", i.e. the general interested audience. The technical version can be found at https://indico.cern.ch/event/1027178/ -> Contribution List -> 11/9/22, 2:00 PM.

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Most of the matter in the universe, 84.3 ± 0.2 %, is in a "dark matter" form that has been "observed" only through its gravitational interaction. As far as we know, this dark matter does not have any other interaction, at least down to the current sensitivity of our experiments and observations. Fritz Zwicky in 1933 found that the matter in the Coma cluster of galaxies greatly exceeds the mass in stars. According to the book by Stefano Profumo, the mass m_h of dark matter particles is unknown over 90 orders of magnitude! In summary, we know exactly how much dark matter there is, but do not have the foggiest idea what it is. And we need dark matter, for without it, no galaxies would have formed, nor would have we.

Let us assume that dark matter is a gas of particles that is ultra-relativistic in the early universe. As the universe expands, dark matter cools, and becomes non-relativistic. We expect that this non-relativistic gas is non-degenerate. Let $v_{h\mathrm{rms}}(a)$ be the root-mean-square velocity of the non-relativistic dark matter particles. a is the expansion parameter of the universe, normalized to $a = 1$ at the present time. To understand the expansion parameter a, imagine a baloon covered with dots. As the baloon is inflated, the distances between neighboring dots, i.e. galaxies, increase in proportion to a. This is how the expansion parameter a is defined. $v^2_{h\mathrm{rms}}(a)$ is proportional to the dark matter temperature-to-mass ratio. As the universe expands, dark matter cools, $v_{h\mathrm{rms}}(a)$ varies in proportion to $1/a$, and the dark matter density $\rho_h(a)$ varies in proportion to $1/a^3$, so

$$v_{h\mathrm{rms}}(1) \equiv v_{h\mathrm{rms}}(a)a = v_{h\mathrm{rms}}(a)\left[\frac{\rho_h(1)}{\rho_h(a)}\right]^{1/3} \tag{1}$$

does not depend on a. In other words, we say that $v_{h\mathrm{rms}}(1)$ is an "adiabatic invariant".

It turns out that, to unravel the dark matter mystery, we need to measure the adiabatic invariant $v_{h\mathrm{rms}}(1)$, and the related observable $k_{\mathrm{fs}} \equiv 2\pi/\lambda_{\mathrm{fs}}$, that we now explain. Due to the velocity dispersion $v_{h\mathrm{rms}}(a)$, dark matter particles free-stream in and out of density minimums and maximums, erasing primordial density fluctuations of "comoving" wavelength less than λ_{fs}. (Since wavelengths grow in proportion to a, it is customary to refer the wavelength to the present time, i.e. $a = 1$, hence the word "comoving".) k_{fs} is the comoving cut-off wavenumber due to dark matter free-streaming. The relation between the two observables, $v_{h\mathrm{rms}}(1)$ and k_{fs}, is summarized in Table 1.

To measure k_{fs} we compare observed and predicted galaxy rest-frame ultra-violet luminosity distributions, and observed and predicted galaxy stellar mass distributions. An example, corresponding to "redshift" $z = 6$, or equivalently, expansion parameter $a = 1/(1+z) = 1/7$, is shown in Figure 1. From this, and similar figures at redshifts $z = 4, 8$ and 10, we obtain $k_{\mathrm{fs}} = 2.0^{+0.8}_{-0.5}$ Mpc^{-1}.

To measure the adiabatic invariant $v_{h\mathrm{rms}}(1)$ we note the following. Consider a free observer in a density peak in the early universe. This observer "sees" dark matter expand adiabatically, i.e. conserving $v_{h\mathrm{rms}}(1)$, due to the expansion of the universe, reach maximum expansion, followed by adiabatic compression into the core of the galaxy due to gravitational attraction. The core of the galaxy forms adiabatically if dark matter is warm as we have assumed, i.e if $v_{h\mathrm{rms}}(1)$ is greater than zero. Rotation and relaxation, due to galaxy collisions and mergers, increase the observed $v'_{h\mathrm{rms}}(1)$ above the true $v_{h\mathrm{rms}}(1)$. So, as long as rotation and relaxation remain negligible, we predict that the adiabatic invariant in the core of the galaxy is the same as in the early universe, and so should be the same for all galaxies (with negligible rotation and relaxation). The adiabatic invariant in the core of a spiral galaxy can be obtained from the observed rotation curves of neutral

Table 1: Calculated relation between the adiabatic invariant $v_{h\rm rms}(1)$, and the comoving cut-off wavenumber $k_{\rm fs}$, due to dark matter free-streaming. “Mega-parsec" (Mpc) is a unit of length used in cosmology.

$v_{h\rm rms}(1)$	$k_{\rm fs}$
750 m/s	1 Mpc^{-1}
490 m/s	1.53 Mpc^{-1}
370 m/s	2 Mpc^{-1}
190 m/s	4 Mpc^{-1}
0.75 m/s	1000 Mpc^{-1}

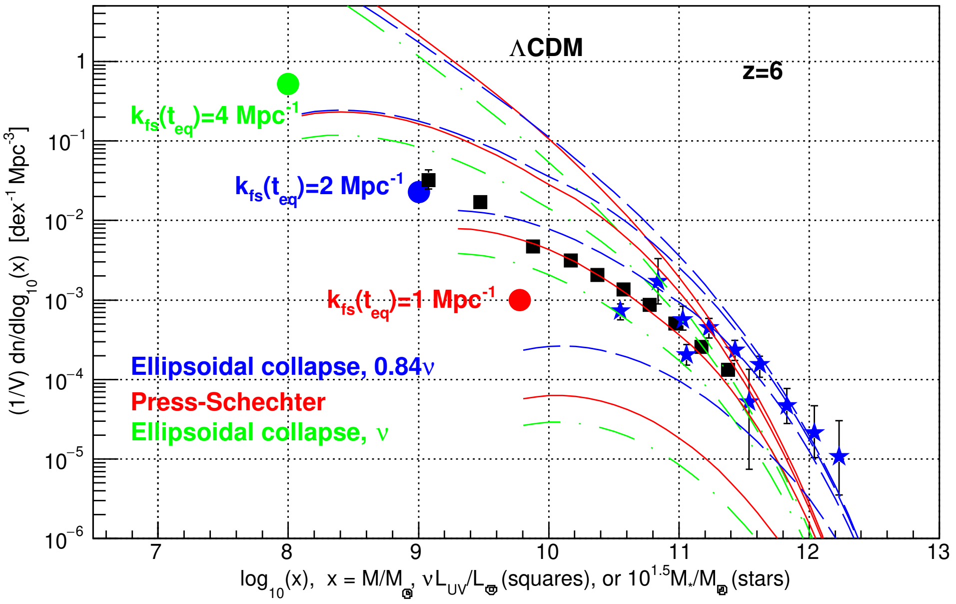

Figure 1: Shown are distributions of x, where x is the observed galaxy stellar mass $M_*/M_\odot$ times $10^{1.5}$ (stars) [1] [2] [3], or the observed galaxy UV luminosity $\nu L_{\rm UV}/L_\odot$ (squares) [4] [5] [6] (corrected for dust extinction [7] [8]), or the predicted linear total (dark matter plus baryon) mass $M/M_\odot$ (lines), at redshift $z = 6$. The symbol $\odot$ means “sun". The Press-Schechter prediction, and its Sheth-Tormen ellipsoidal collapse extensions, correspond, from top to bottom, to the warm dark matter free-streaming cut-off wavenumbers $k_{\rm fs} = 1000, 4, 2$ and 1 Mpc^{-1}. The round red, blue and green dots indicate the velocity dispersion cut-offs of the predictions [9] at $k_{\rm fs} = 1, 2$ and 4 Mpc^{-1}, respectively. Presenting three predictions illustrates the uncertainty of the predictions. Note that the data agree with predictions for $k_{\rm fs} \approx 2$ Mpc^{-1}.

atomic hydrogen gas, together with infrared and visible images. The distribution of the adiabatic invariant measured in several dwarf galaxies is shown in Figure 2. We obtain a narrow peak with $v_{h\mathrm{rms}}(1) = 406 \pm 69$ m/s. Galaxies with $v'_{h\mathrm{rms}}(1)$ to the right of this peak have significant rotation and/or relaxation.

We note, from Table 1, that the measurements of k_{fs} and $v_{h\mathrm{rms}}(1)$ are consistent with each other, demonstrating that (1) $v_{h\mathrm{rms}}(1)$ in the core of galaxies (corrected for dark matter rotation and relaxation) is of cosmological origin, as inferred form the narrowness of the peak in Figure 2, and as predicted for warm dark matter; and (2) that k_{fs} is indeed due to dark matter particle free-streaming. Let us mention that the entire analysis is data driven, with full details, and the sources of all data and measurements, available in the references below.

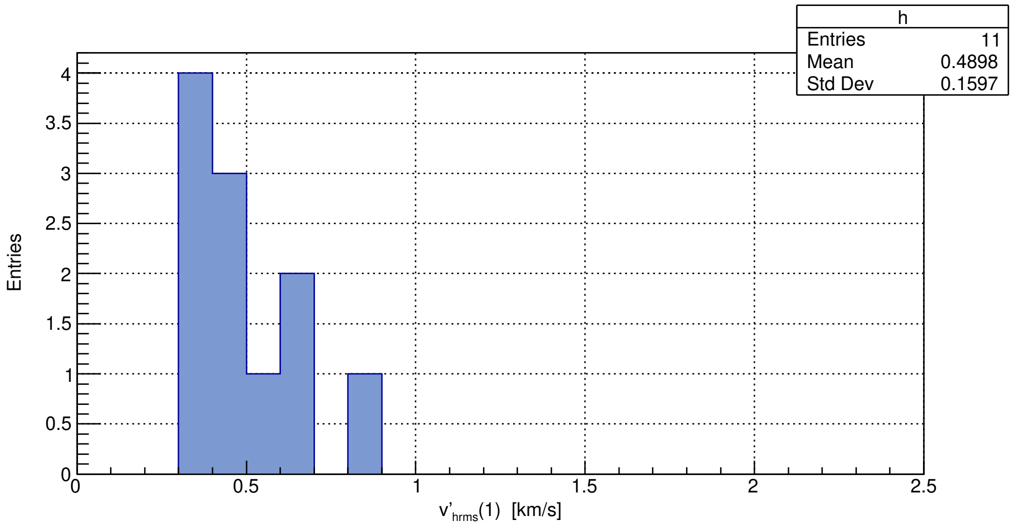

Figure 2: Distribution of $v'_{h\mathrm{rms}}(1)$, i.e. the adiabatic invariant before the dark matter rotation and relaxation correction, of 11 dwarf galaxies. These corrections can only be negative, and so are negligible in the peak at $v'_{h\mathrm{rms}}(1) \approx v_{h\mathrm{rms}}(1) \approx 0.4$ km/s. Data from [10].

The cold dark matter ΛCDM theory, with only six parameters, is in spectacular agreement with the large scale phenomena of the “Cosmic Microwave Background Radiation", “Baryon Acoustic Oscillations", and the large scale matter distribution in the universe. However, there are, or appear to be, tensions with small scale phenomena, less than the size of a galaxy, known as the “Core-Cusp Problem", the “Missing Satellites Problem", the “Angular Momentum Catastrophe", and the rest frame ultra-violet luminosity cut-off required to not exceed the “Reionization Optical Depth" measured by the Planck collaboration. Adding to the cold dark matter ΛCDM theory one more parameter, namely the adiabatic invariant $v_{h\mathrm{rms}}(1)$, obtains the warm dark matter ΛWDM cosmology. It turns out that ΛWDM agrees with ΛCDM on large scales, and, with the measured $v_{h\mathrm{rms}}(1)$ and k_{fs} indicated above, solves all of the mentioned small scale tensions.

And now comes the miracle: the measured k_{fs} and $v_{h\mathrm{rms}}(1)$ happen to coincide with the expectations of the “no freeze-in and no freeze-out" scenario of spin zero dark matter particles that decouple early on from the Standard Model sector, e.g. dark matter particles coupled to the

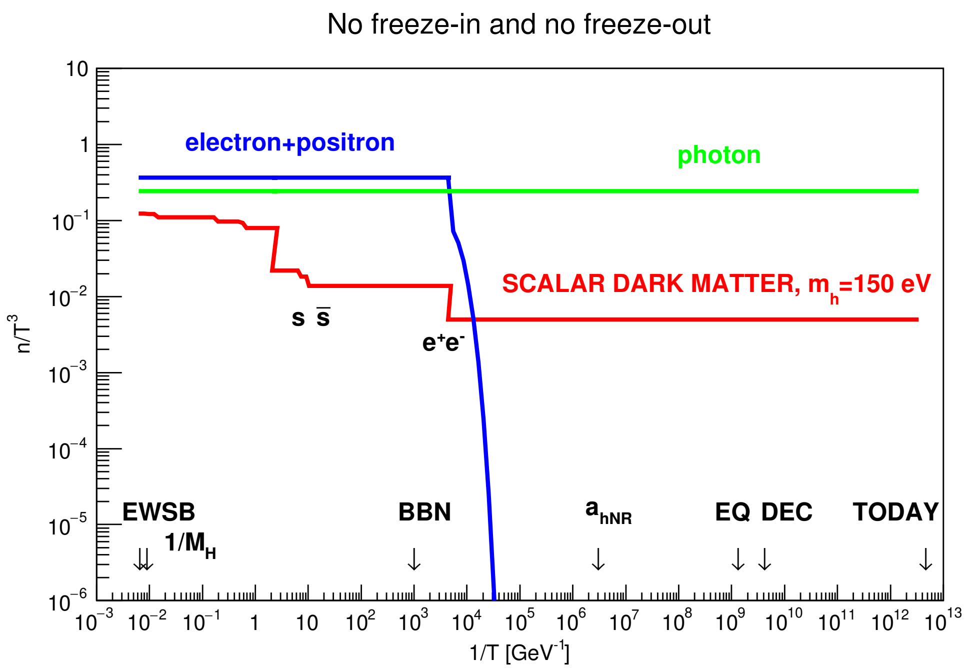

Figure 3: The "no freeze-in and no freeze-out" warm dark matter scenario is illustrated for spin zero warm dark matter particles coupled to the Higgs boson. T is the photon temperature, and the n's are particle number densities. The abreviations stand for "Electro-Weak Symmetry Breaking", "Big Bang Nucleosynthesis", "EQuivalence" of matter and radiation densities, and "DECoupling" of photons from matter. Dark matter particles become non-relativistic at $a_{h\mathrm{NR}}$. Time advances towards the right.

Higgs boson, or to the top quark, or to the W or Z bosons. Let me explain. "No freeze-in" means that dark matter is in thermal and diffusive, i.e. chemical, equilibrium, in the early universe, with the particles of the "Standard Model of Quarks and Leptons", or, loosely speaking, with ordinary matter. Dark matter then decouples from the Standard Model sector while still ultra-relativistic. "No freeze-out" means that, when dark matter becomes non-relativistic, its mutual interactions are so weak that these particles do not annihilate each other. An example of spin zero dark matter coupled to the Higgs boson is shown in Figure 3. If dark matter is indeed coupled to the Higgs boson, then the no freeze-in and no freeze-out scenario predicts $v_{h\mathrm{rms}}(1) = 490 \pm 10$ m/s and $k_{\mathrm{fs}} = 1.53 \pm 0.03$ Mpc^{-1}, and the mass of the dark matter particles $m_h = 150 \pm 2$ eV (or about $1/3400$ of the electron mass). For couplings to other massive Standard Model particles, the predictions vary slightly. The data strongly disfavors spin one-half and spin one dark matter.

In summary, we arrive at a plausible, data driven, and detailed solution to the dark matter mystery. Quite fantastic! [1]

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[1] For technical details see [11] [12] [13] [14] [15].

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