The mass of the dark matter particle from theory, galaxy observations and N-body simulations

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A new analysis of dark matter, combining theory, astronomical observations of dwarf spheroidal satellite galaxies in the Milky Way and N-body numerical simulations allows to determine the mass of the dark matter particle which turns to be at the keV scale (1 keV = 1000 eV) and the temperature when the dark matter decoupled from ordinary matter and radiation, which turns to be 100 GeV at least. Two scientists of the Observatoire de Paris and the Université Pierre et Marie Curie performed a *model independent* analysis of dark matter and established a direct connection between the microphysics of the dark matter decoupling from ordinary matter and radiation in the early universe and the conditions that particles must fulfill to be suitable dark matter candidates for galaxy formation and observations. In all cases: for dark matter particles decoupling either ultra-relativistic or non-relativistic, both at local thermal equilibrium or out of local thermal equilibrium, they found : (i) the mass of the dark matter particle is in the keV scale, the decoupling temperature is 100 GeV at least and dark matter particles are cold. (ii) The free-streaming (Jeans') wavelength today is in the kpc range, consistent with the observed small scale structure and the Jean's mass is in the range of the galactic masses, $10^{12} M_\odot$. (iii) The dark matter annihilation or self-interaction cross-section (different than gravity) is negligable. (iv) The keV scale mass dark matter determines cored (non cusped) dark matter halos. (v) Dark matter particle candidates with typical high masses $\gtrsim 100$ GeV, so called "wimps" (weakly interacting massive particles) result strongly disfavored.

Although dark matter was noticed seventy-five years ago (Zwicky 1933, Oort 1940) its nature is not yet known. Dark matter represents about 23.4 % of the matter of the universe. Dark matter is different from atoms, does not emit or absorb light and it has only been detected indirectly through its gravitational action. The clustering properties of collisionless dark matter candidates in the linear regime depend on the free streaming length, which roughly corresponds to the Jeans length with the particle's velocity dispersion replacing the speed of sound in the gas. Cold DM (CDM) candidates feature a small free streaming length favoring a bottom-up hierarchical approach to structure formation, smaller structures form first and mergers lead to clustering on the larger scales. The *concordance* ΛCDM standard cosmological model emerging from the cosmic microwave background and large scale structure observations and simulations favors dark matter composed of primordial particles which are cold and collisionless. Compilation of observations of dwarf spheroidal galaxies dSphs, which are considered to be prime candidates for DM subtructure, are compatible with a core of smoother central density and a low mean mass density $\sim 0.1\, M_\odot/\text{pc}^3$ rather than with a cusp .

Dark matter particles can decouple being ultrarelativistic or non-relativistic. Dark matter must be non-relativistic by the time of structure formation at redshifts $z < 30$ in order to reproduce the observed small structure at $\sim 2 - 3$ kpc. In addition, the decoupling can occurs at local thermal equilibrium or out of local thermal equilibrium. All these cases have been considered in this work: From first principles and the distribution function of dark matter particles with their different statistics, physical magnitudes as the dark matter energy density $\rho_{DM}(z)$, the dark matter velocity dispersion $\sigma_{DM}(z)$, the dark matter density in the phase space $\mathcal{D}(z)$ are analitically computed and confronted to their values observed today ($z = 0$). From them, the mass m of the dark matter particle and its decoupling temperature T_d are obtained. The phase-space density today is a factor Z smaller than its primordial value. The decreasing factor $Z > 1$ is due to the effect of non-linear self-gravity interactions: the range of Z is here computed both analytically and numerically. The dark matter energy density observed today has the value $\rho_{DM} = 0.228\ (2.518\ \text{meV})^4$. In addition, compilation of dwarf spheroidal satellite galaxies observations in the Milky Way yield the one dimensional velocity dispersion σ_s and the radius L in the ranges $6.6\ \text{km/s} \leq \sigma_s \leq 11.1\ \text{km/s}$, $\quad 0.5\ \text{kpc} \leq L \leq 1.8\ \text{kpc}$ and the phase-space density today (with a precision of a factor 10) has the value : $\mathcal{D}(0) \sim 5 \times 10^3\ \frac{\text{keV/cm}^3}{(\text{km/s})^3} = (0.18\ \text{keV})^4$.

In this framework, the results obtained in this work are the following:

- The self-gravity reduction factor Z of the phase space density $\mathcal{D}(z)$ is in the range

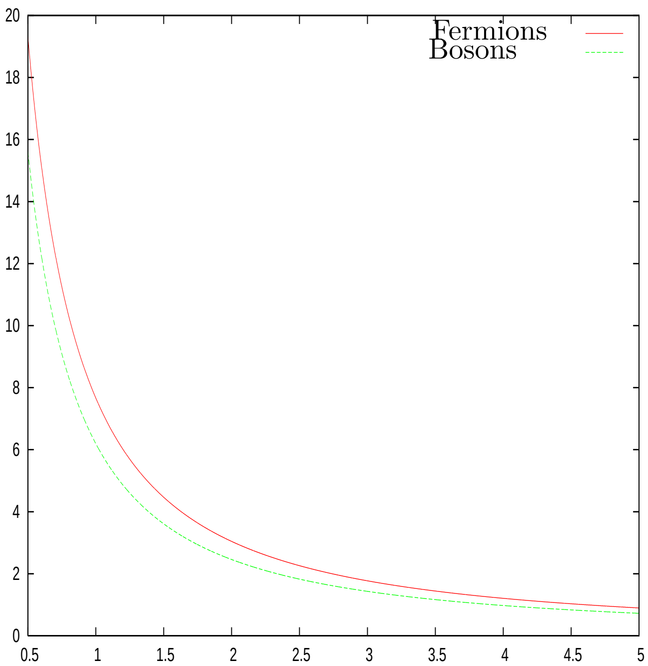

FIG. 1: The free-streaming (Jeans) wavelength today $\lambda_{fs}(0)$ in kpc vs. the dark matter particle mass m in keV. $\lambda_{fs}(0)$ decreases for increasing mass m and shows little variation with the particle statistics (fermions or bosons). For m in the keV scale, $\lambda_{fs}(0)$ is in the kpc scale, of the order of the small dark matter structures observed today.

$1 < Z < 10000$ for dwarf spheroidal galaxies dSphs. More accurate analysis of N body simulations should narrow this range which depends on the type and size of the galaxy considered. Our formulae indicate a sharp decrease of the phase-space density with the redshift. This sharp decreasing is in agreement with the simulations in the violent merger phases followed by quiescent phases.

- The mass of the dark matter particle, **independent** of the particle model, is in the keV scale and the temperature when the dark matter particles decoupled is in the 100 GeV scale at least. No assumption about the nature of the dark matter particle is made. The keV range DM particle mass is much larger than the temperature during the matter dominated era (which is less than 1 eV), hence the keV dark matter is **cold** (CDM). The dark matter particle mass m and decoupling temperature T_d are **mildly** affected by the uncertainty in the factor Z through a power factor 1/4 of this uncertainty, namely, by a factor $10^{\frac{1}{4}} \simeq 1.8$.

- The comoving Jeans' (free-streaming) wavelength, ie the largest wavevector exhibiting gravitational instability (Fig. 1), and the Jeans' mass (the smallest unstable mass by gravitational collapse) are obtained in the range

$$\frac{0.76}{\sqrt{1+z}} \text{ kpc} < \lambda_{fs}(z) < \frac{16.3}{\sqrt{1+z}} \text{ kpc} \; , \; 0.45 \; 10^3 \; M_\odot < \frac{M_J(z)}{(1+z)^{+\frac{3}{2}}} < 0.45 \; 10^7 \;\; M_\odot \; .$$

These values at $z = 0$ are consistent with the N-body simulations and are of the order of the small dark matter structures observed today . By the beginning of the matter dominated era $z \sim 3200$, the masses are of the order of galactic masses $\sim 10^{12} \; M_\odot$ and the comoving free-streaming wavelength scale turns to be of the order of the galaxy sizes today ~ 100 kpc ,.

- Lower and upper bounds for the dark matter annihilation cross-section σ_0 are derived: $\sigma_0 > (0.239 - 0.956) \; 10^{-9} \; \text{GeV}^{-2}$ and $\sigma_0 < 3200 \; m \; \text{GeV}^{-3}$. There is at least five orders of magnitude between them , the dark matter non-gravitational self-interaction is therefore negligible (consistent with structure formation and observations, as well as by comparing X-ray, optical and lensing observations of the merging of galaxy clusters with N-body simulations).

- Typical "wimps" (weakly interacting massive particles) with mass $m = 100$ GeV and $T_d = 5$ GeV would require a huge $Z \sim 10^{23}$, well above the upper bounds obtained and cannot reproduce the observed galaxy properties. They produce an extremely short free-streaming or Jeans length λ_{fs} today $\lambda_{fs}(0) \sim 3.51 \; 10^{-4}$ pc $= 72.4$ AU that would correspond to unobserved structures much smaller than the galaxy structure. Wimps result strongly disfavoured.

Reference

H. J. de Vega, N. G. Sanchez, 'Model-independent analysis of dark matter points to a particle mass at the keV scale', MNRAS, May 2010 issue.

Further reading:

D Boyanovsky, H. J. de Vega, N.G. Sanchez 'Constraints on dark matter particles from theory, galaxy observations and N-body simulations', Phys. Rev. **D77** : 043518, 2008.

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