Universe
2021
WEBINARS
keV Warm Dark Matter in Agreement with Observations in Tribute to Héctor J. De Vega
10 NOVEMBER 2021, 1:30 PM (CET)
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Relevant Universe Special Issue:

keV Warm Dark Matter (ΛWDM) in Agreement with Observations in Tribute to Héctor J. de Vega

https://chalonge-devega.fr/HdeV.html

Deadline for manuscript submissions:

30 November 2021

https://www.mdpi.com/journal/universe/special_issues/kWDM

Welcome to the Webinar "keV Warm Dark Matter in Agreement with Observations in Tribute to Hector J. de Vega

keV-Warm Dark Matter (WDM) research is progressing rapidly; the subject is new and essentially works by naturally reproducing the astronomical observations over all scales: small and intermediate galactic scales and large (cosmological) scales (ΛWDM).

This webinar highlights the contents of the Special Issue devoted to this subject and the new results presented within it, with the aim of clarification and synthesis by combining theory, analysis, observation, and numerical simulations in a conceptual framework.

We host talks presenting new results as well reviews plus this Introduction: DM Sterile Neutrinos: Production Mechanisms in the Early Universe ; New Bounds for the Mass of the Warm Dark Matter Particles Using Results from Fermionic King Model; Axion-Sterile-Neutrino Dark Matter; The Epoch of Reionization in Warm ark Matter scenarios; Fundamental properties of the dark and the luminous matter from the Low Surface Brightness discs. This offers an updated collection of new results, reviews and new research lines in this highly active field and its implications in sterile neutrinos, galaxies, and cosmology, with both theory and observations.

Speaker/ Presentation	Time in CEST/CET
Chair Prof. Norma G. Sanchez keV Warm Dark Matter in Agreement with Observations In Tribute to Hector de Vega	1:30 – 2.00 pm
Prof. Daniel Boyanovsky Light sterile neutrinos from the cosmological decay of pions in the Early Universe	2:00 – 2:30 pm
Dr. Luisberis Velazquez Abad New bounds for the mass of warm dark matter particles using results from fermionic King model	2:30 – 3:00 pm
Dr. Alberto Salvio Axion-Sterile-Neutrino Dark Matter	3:00 – 3:30 pm
Dr. Nicola Menci, Massimiliano Romanello The Epoch of Reionization in Warm Dark Matter scenarios	3:30 – 4:00 pm
Prof. Paolo Salucci Fundamental properties of the dark and the luminous matter from the Low Surface Brightness discs	4:00 – 4:30 pm
Q&A Session and Closing of the Webinar	4:30 – 4:40 pm

Warm Dark Matter Cosmology (LWDM)

Basement- ground Zero

Dark matter is the dominant component of Galaxies and is an essential ingredient to understand Galaxy properties and Galaxy formation

Dark matter and Galaxy Formation must be treated within a cosmological context

The nature (the type) of Dark Matter and the cosmological model need to be explicitated when discussing galaxies and galaxy formation

All the building of galaxy formation depends on

the nature of Dark Matter

Dark Matter in the Universe

→ 81 % of the matter of the universe is DARK (DM).
→ DM is the dominant component of galaxies.
→ DM interacts through gravity.

→ Further DM interactions unobserved so far.
Such couplings must be very weak: much weaker than weak interactions.
→ DM is outside the Standard Model of Particle Physics.

Proposed candidates:
Cold Dark Matter: CDM, WIMPS, m ~ 1 − 1000 GeV: IN BIG TROUBLE.

→ Warm Dark Matter: WDM, sterile neutrinos, m ~ keV
THE ANSWER !

→ DM particles decouple due to the universe expansion, their distribution function freezes out at decoupling.
→ Early decoupling: Td ~ 100 GeV

WDM properties

WDM is characterized by

- its initial power spectrum cutted off for scales below ~ 50 kpc. Thus, structures are not formed in WDM for scales below ~ 50 kpc.
- its initial velocity dispersion. However, this is negligible for $z < 20$ where the non-linear regime starts.
- Classical N-body simulations break down at small distances ($\sim$ pc). Need of quantum calculations to find WDM cores.

Structure formation is hierarchical in CDM.

WDM simulations show in addition top-hat structure formation at large scales and low densities but hierarchical structure formation remains dominant.

Summary Warm Dark Matter, WDM: $m \sim$ keV

- Large Scales, structures beyond ~ 100 kpc: WDM and CDM yield identical results which agree with observations
- Intermediate Scales: WDM simulations give the correct abundance of substructures.
- Inside galaxy cores, below ~ 100 pc: N-body classical physics simulations are incorrect for WDM because of important quantum effects.
- Quantum calculations (Thomas-Fermi) give galaxy cores, galaxy masses, velocity dispersions and densities in agreement with the observations.
- Direct Detection of the main WDM candidate: the sterile neutrino. Beta decay and electron capture. ^{3}H, Re, Ho.

So far, not a single valid objection arose against WDM.
Baryons (<16%DM) expected to give a correction to WDM

UPDATE and CLARIFICATIONS

→ΛCDM agrees with CMB + LSS **BUT**
ΛCDM **DOES NOT agree with SSS (GALAXIES)**

→ **ΛWDM** agrees with CMB + LSS + SSS (GALAXIES)
The Standard Model of the Universe is LWDM =
{GR, Newtonian Gravity, Field Theory, QFT}

Sentences like « CMB confirms the ΛCDM model … »
Must be completed by adding: « in the large scales" »
and must be updated with the sentence:
→ **CMB confirms the ΛWDM model in large scales**

NEW: Gravity and Quantum Mechanics in Galaxies. Newton, Fermi and Dirac meet together in Galaxies because of keV WDM

→**WDM solves naturally the problems of CDM and CDM + baryons , provides the same large scale and CMB results than ΛCDM and agrees with the observations at the galactic and small scales.**

→**Warm Dark Matter Cosmology (ΛWDM) is more complete, correct and general theory than Cold Dark Matter (LCDM) because it contains CDM as a limiting case (for high particle masses), reproduces LCDM at large scales and solves the known problems of CDM at small and intermediate scales.**

→**So far, not a single valid objection arose against WDM.**

ΛWDM Cosmology

(I) The Standard Model of the Universe Includes Inflation

(II) DARK MATTER IN GALAXIES from Theory and Observations: Warm (keV scale) DM

(III) NOVEL: THE ESSENTIAL ROLE OF QUANTUM PHYSICS IN WDM GALAXIES:

Semiclassical framework: Analytical Results and Numerical (including analytical) Results

Observed Galaxy cores and structures from Fermionic WDM and more results.

(IV) NEW: The generic Galaxy types and properties from a same physical framework: From quantum (compact, dwarfs) to classical (dilute, large) galaxies. Equation of state. Generalized Eddington approach to galaxies

(V) The case for the keV sterile neutrino

DARK MATTER UPDATE

- **THERE IS NO CUSP/CORE problem:**
- **Observed Galaxy density profiles are cored.**
- **WDM Galaxy density profiles are cored**

- **THERE IS NO satellite problem**
- **WDM abundance of structures agrees with observations**
- **In addition, these are not fundamental problems.**

NO CDM Wimps, NO DM annhilation,

The Total DM cannot be bosons (Axions)

Structure Formation in the Universe

Structures in the Universe as galaxies and cluster of galaxies form out of the small primordial quantum fluctuations originated by inflation just after the big-bang.

These linear small primordial fluctuations grow due to gravitational unstabilities (Jeans) and then classicalize.

Structures form through non-linear gravitational evolution.

Hierarchical formation starts from small scales first.

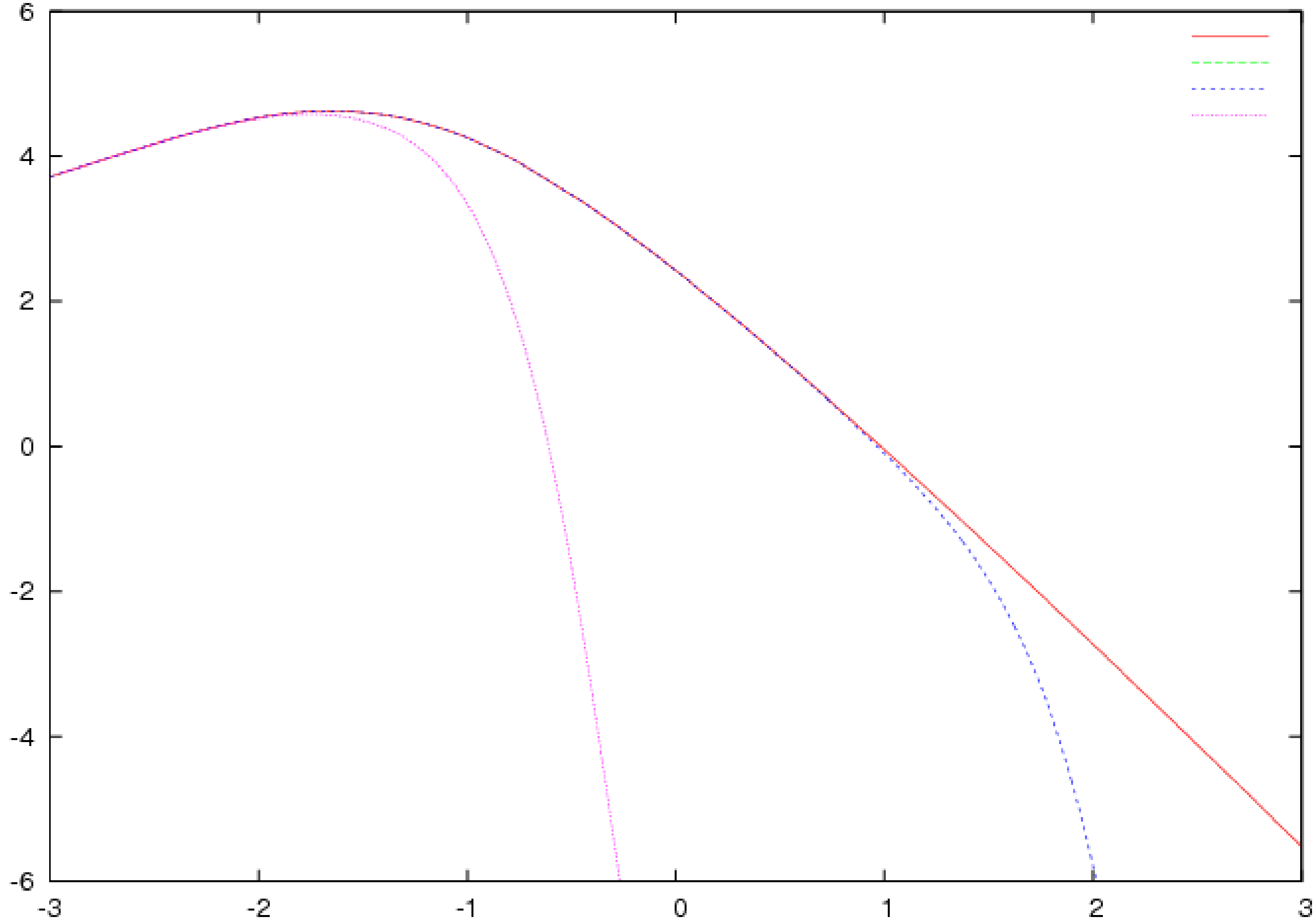
N-body CDM simulations fail to produce the observed structures for small scales less than some kpc.

Both N-body WDM and CDM simulations yield identical and correct structures for scales larger than some kpc.

WDM predicts correct structures for small scales (below kpc) when its quantum nature is taken into account.

Primordial power $P(k)$: first ingredient in galaxy formation.

Linear primordial power today $P(k)$ vs. k Mpc h

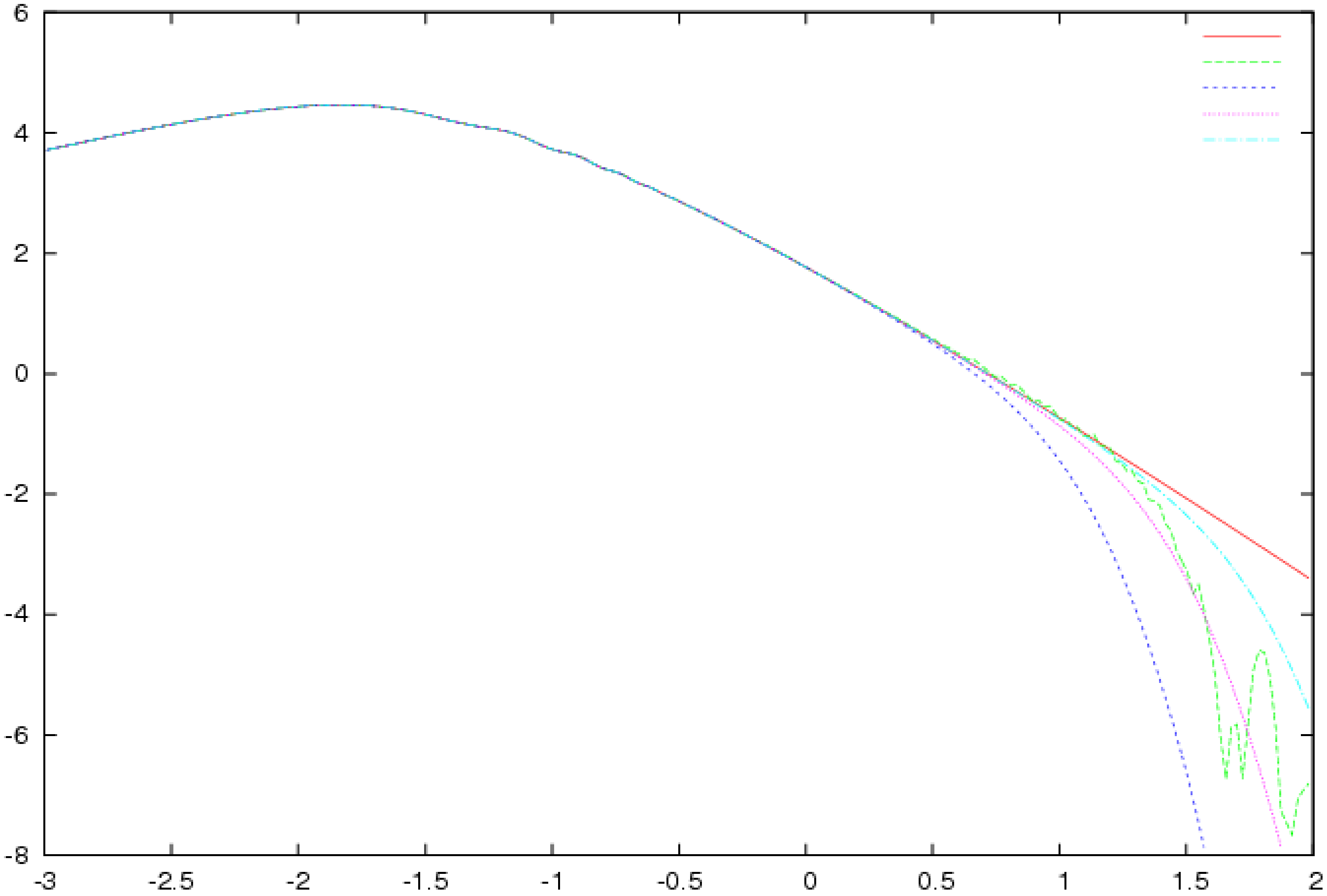


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS, 1 keV DM particles and 10 eV DM particles. $P(k) = P_0 \, k^{n_s} \, T^2(k)$.

$P(k)$ cutted for 1 keV DM particles on scales $\lesssim 100$ kpc.

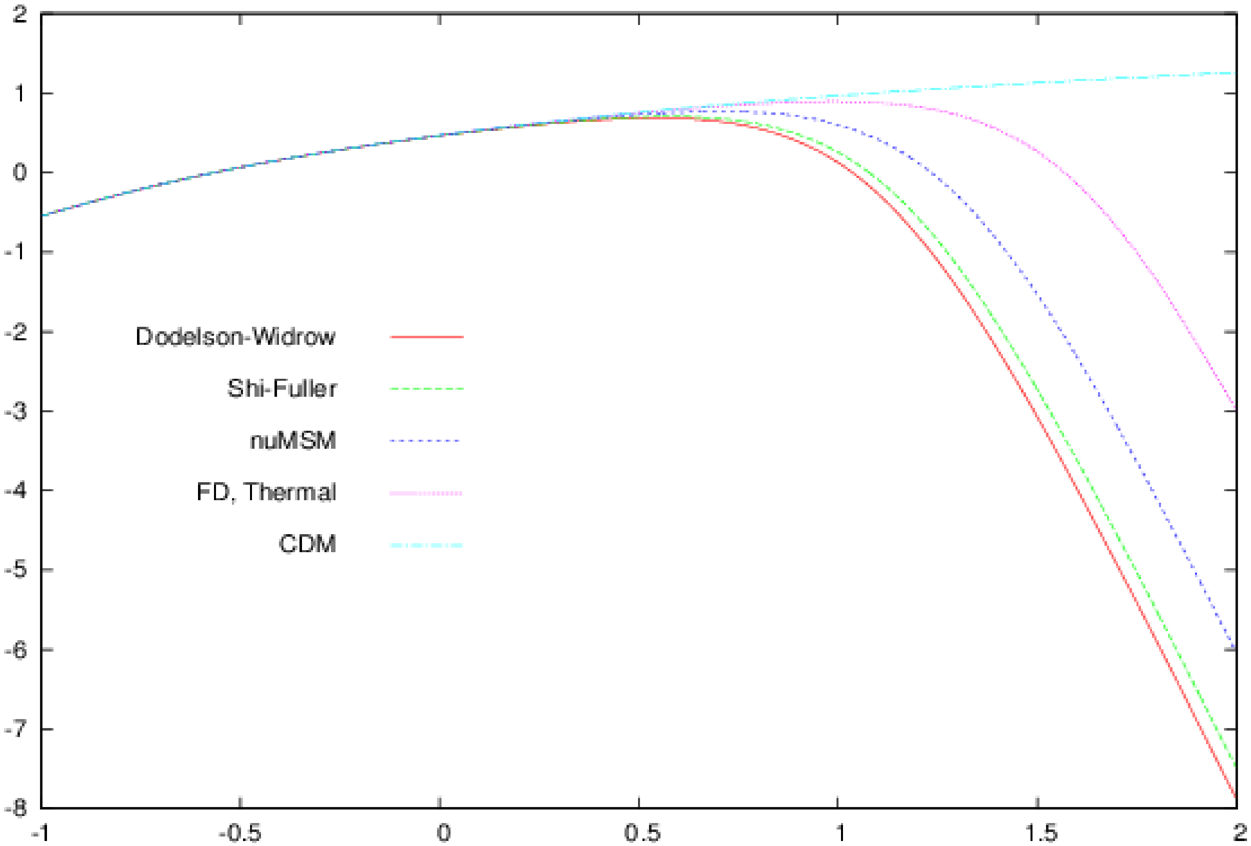
Transfer function in the MD era from Gilbert integral eq

Linear primordial power today $P(k)$ vs. k Mpc h



$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for CDM, 1 keV, 2 keV, light-blue 4 keV DM particles decoupling in equil, and 1 keV sterile neutrinos. WDM cuts $P(k)$ on small scales $r \lesssim 100 \, (\text{keV}/m)^{4/3}$ kpc. CDM and WDM identical for CMB.

Linear primordial power spectrum $\Delta^2(k)$ vs. k Mpc $/h$



$\log_{10} \Delta^2(k)$ vs. $\log_{10}[k \text{ Mpc}/h]$ for a physical mass of 2.5 keV in four different WDM models and in CDM. WDM cuts $\Delta^2(k)$ on small scales. $r \lesssim 73 \, (\text{keV}/m)^{1.45}$ kpc/h.
CDM and WDM are identical for CMB.

WDM free streaming scale

The scale $l_{1/2}$ is where the WDM power spectrum is one-half of the CDM power spectrum:

$$l_{1/2} = 1/k_{1/2} = 207 \text{ kpc } \left(\text{keV}/m_{FD}\right)^{1.12}$$

This scale reproduces the sizes of the observed DM galaxy cores when the WDM mass is in the keV scale !!

$l_{1/2}$ is similar but more precise than the free streaming scale (or Jeans' scale):

$$r_{Jeans} = 210 \, \text{kpc} \, \frac{\text{keV}}{m_{FD}} \left(\frac{100}{g_d}\right)^{\frac{1}{3}} ,$$

$g_d =$ number of UR degrees of freedom at decoupling.

he Phase-space density $Q = \rho/\sigma^3$ and its decrease factor

The phase-space density today Q_{today} follows observing dwarf spheroidal satellite galaxies of the Milky Way (dSphs) as well as spiral galaxies. Its value is galaxy dependent.

For dSphs $Q_{today} \sim 5000 \; (0.18 \text{ keV})^4$ Gilmore et al. 07/08.

During structure formation Q decreases by a factor that we call Z, $(Z > 1)$: $Q_{today} = \frac{1}{Z} \, Q_{prim}$

The spherical model gives $Z \simeq 41000$ and N-body simulations indicate: $10000 > Z > 1$. Z is galaxy dependent.

As a consequence m is in the keV scale:
1 keV $\lesssim m \lesssim 10$ keV.

This is true both for DM decoupling in or out of equilibrium, bosons or fermions.
It is independent of the particle physics model.

de Vega Sanchez – Theory Approach to Galaxy Structure

FERMIONIC QUANTUM WDM and GRAVITATION DETERMINE THE OBSERVED PHYSICAL GALAXY STRUCTURE

→ **Dark matter (DM): main component of galaxies. Quantum mechanics: cornerstone of physics from microscopic to macroscopic systems: quantum liquids He3, white dwarf stars, neutron stars, BHs: NOT Exotic Physics.**

→ **Quantum mechanics also responsible of galaxy structures at the kpc scales and below: near the galaxy center, below 10 - 100 pc, the DM quantum effects important for warm DM (WDM), that is for DM particles with masses in the keV scale.** MNRAS 2010 , NA2013 , JAP2013, dVS PRD 2013, dVSS MNRAS 2014, EPJC 2016, IJMPA 2016,

→ **Approach to galaxy structure with results in remarkable agreement with observations:**

Quantum Bounds on Fermionic Dark Matter

The Pauli principle gives the upper bound to the phase space distribution function of spin-$\frac{1}{2}$ particles of mass m:

$$f(\vec{r},\vec{p}) \leq 2$$

The DM mass density is given by:

$$\rho(\vec{r}) = m \int d^3p \, \frac{f(\vec{r},\vec{p})}{(2\,\pi\,\hbar)^3} = \frac{m^4}{2\,\hbar^3}\,\sigma^3(\vec{r})\,\bar{f}(\vec{r})\,K \;,$$

where:

$\bar{f}(\vec{r})$ is the $\vec{p}-$average of $f(\vec{r},\vec{p})$ over a volume $m^3\,\sigma^3(\vec{r})$,

$\sigma(\vec{r})$ is the DM velocity dispersion, $\sigma^2(\vec{r}) \equiv < v^2(\vec{r}) > /3$

$K \sim 1$ a pure number.

The Pauli bound $\bar{f}(\vec{r}) \leq 2$ yields: $Q(\vec{r}) \equiv \frac{\rho(\vec{r})}{\sigma^3(\vec{r})} \leq K\,\frac{m^4}{\hbar^3}$

This is an absolute quantum upper bound on $Q(\vec{r})$ due to quantum physics, namely the Pauli principle.

$Q(\vec{r})$ can **never** take values larger than $K\,m^4/\hbar^3$.

In the classical limit $\hbar \to 0$ and the bound disappears.

Classical physics breaks down near the galaxy center

N-body simulations point to cuspy phase-space densities

$Q(r) = Q_s \left(\frac{r}{r_s}\right)^{-\beta}$, $\beta \simeq 1.9 - 2$, $r_s =$ halo radius,

$Q_s =$ mean phase space density in the halo.

$Q(r)$ derived within classical physics tends to infinity for $r \to 0$ violating the Pauli principle bound.

Classical physics breaks down near the galaxy center.

For $\beta = 2$ the quantum upper bound on $Q(r)$ is valid for

$$r \geq r_q \equiv \frac{\hbar^{\frac{3}{2}}}{m^2} \sqrt{\frac{Q_s}{K}}\, r_s \ .$$

Observations yield: $30 < \frac{r_s}{\text{pc}} < 5.10^4$, $2.10^{-5} < \frac{\hbar^{\frac{3}{2}} \sqrt{Q_s}}{(\text{keV})^2} < 0.6$

The larger Q_s and the smaller r_s correspond to ultra compact dwarfs

The smaller Q_s and the larger r_s correspond to spirals.

Dwarf galaxies as quantum objects

de Broglie wavelength of DM particles $\lambda_{dB} = \frac{\hbar}{m\,\sigma}$

$d =$ mean distance between particles,
$\sigma =$ DM mean velocity

$$d = \left(\frac{m}{\rho}\right)^{\frac{1}{3}} \quad , \quad Q = \rho/\sigma^3 \quad , \quad Q = \text{phase space density.}$$

ratio: $\mathcal{R} = \frac{\lambda_{dB}}{d} = \hbar \left(\frac{Q}{m^4}\right)^{\frac{1}{3}}$

Observed values: $2 \times 10^{-3} < \mathcal{R} \left(\frac{m}{\mathrm{keV}}\right)^{\frac{1}{3}} < 1.4$

The larger $\mathcal{R}$ is for ultracompact dwarfs.
The smaller $\mathcal{R}$ is for big spirals.

$\mathcal{R}$ near unity (or above) means a QUANTUM OBJECT.

Observations alone show that compact dwarf galaxies are quantum objects (for WDM).

The quantum radius r_q for different kinds of DM

DM type	DM particle mass	r_q	
CDM	$1 - 100$ GeV	$1 - 10^4$ meters	in practice zero
WDM	$1 - 10$ keV	$0.1 - 1$ pc	compatible with observed cores
HDM	$1 - 10$ eV	kpc - Mpc	too big !

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

(1) Dwarf galaxies are quantum macroscopic objects for WDM supported against gravity by the WDM fermion pressure

(2) Theoretical analytic framework based on Thomas-Fermi approach 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.

(3) Interestingly enough, a minimal galaxy 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.

- OBSERVED GALAXY CORES vs CDM CUSPS and WDM CORES-

- **Well established sets of 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 Physics N-body WDM simulations exhibit cores but with sizes much smaller than the observed cores.

We have recently developped a new approach to this problem thanks to Quantum Mechanics.

- **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.**

THE MINIMAL GALAXY MASS

A minimal galaxy mass and minimal velocity dispersion are found. Mmin ~ 3.1 10^4 Msun

This in turn implies a minimal mass m_{min} = 1.91 keV 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 O(keV).

More precise data will make this estimation more precise.

RESULTS

All the obtained density profiles are cored.

The Core Sizes are in agreement with the observations from the compact galaxies where r_h ~ 20 pc till the spiral and elliptical galaxies where r_h ~ 0.2 - 60 kpc.

The larger and positive is the chemical potential ν(0), the smaller is the core.

The minimal one arises in the degenerate case ν(0) --> to +infinity (compact dwarf galaxies).

And The Phase-space Density

The Galaxy halo Masses.

Agreement is found in all the range of galaxies for a DM particle mass m in the keV scale.

WDM THEORY OF GALAXIES
REPRODUCES THE OBSERVED GALAXY STRUCTURES

Gravity and Quantum Mechanics meet together in Galaxies

de Vega, Salucci, Sanchez 2014 reproduced, with a physical theory to the main observed properties of galaxies of all types, masses and sizes, as the rotation curves, density profiles, phase space density, and scaling relations between the galaxy masses, sizes and velocities galaxy structure which captures the essential ingredients of galaxies: dark matter and gravity.

Newton, Fermi and Dirac, meet together in Galaxies through Warm Dark Matter

This new framework requires dark matter particles to be fermionic with mass in the scale of kilo Volts (keV "warm dark matter") and described by their quantum mechanical properties, as their quantum pressure resulting from the combination of the Pauli exclusion principle and the Heisenberg uncertainty principle.

Compact dwarf galaxies are thus near the Fermi gas degenerate regime, while large dilute galaxies are in the classical gas Boltzmann regime.

This approach corresponds to the Schrödinger equation in the large number of particles regime and is for galaxies the analogue of the Thomas-Fermi approach for atoms, with gravitation instead of the electric potential.

Universal rotation curves and Universal density profiles: The same for all large galaxies

The theoretically obtained galaxy rotation curves and density profiles reproduce extremely well the observational curves from ten different and independent sets of data for galaxy

Masses from 5×10^{9} Msun till 5×10^{11} Msun.

Remarkably enough, the normalized theoretical circular velocities and density profiles are universal (URC): they are the same for all galaxies of different types, sizes and masses, and they agree extremely well with the observational curves described by cored profiles (flat smooth profiles at the center) and their sizes.

Interestingly enough, small deviations from the exact scaling relations show up for compact dwarf galaxies as a manifestation of the quantum macroscopic effects present in these galaxies.

Robust Results

Results of this work are independent of any particular warm dark matter particle physics model, they only follow from the self-gravitation of the warm dark matter particles and their fermionic nature. These important results show the ability of this approach to describe the galaxy structures. They also show that baryonic corrections are not very important to warm dark matter, consistent with the fact that dark matter is in average at least six times more abundant than baryons. The fraction of dark matter over the total mass of galaxies goes from the 95% for large dilute galaxies till 99.99% for dwarf compact galaxies. The baryon fraction in large galaxies can only reach values up to 5 %.

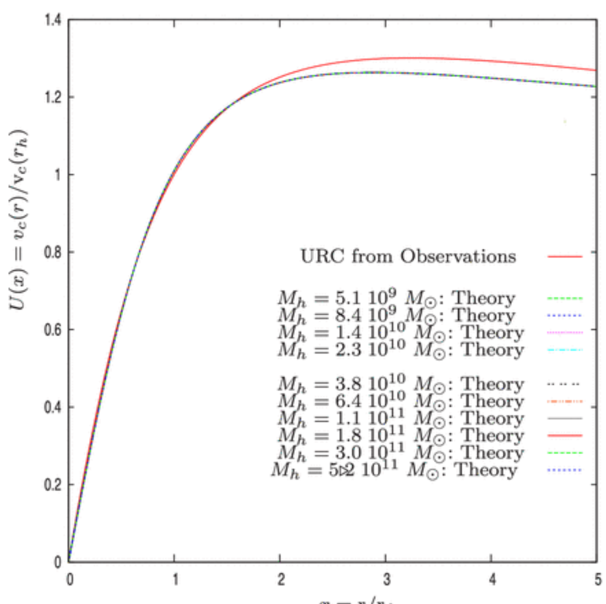
Reference:

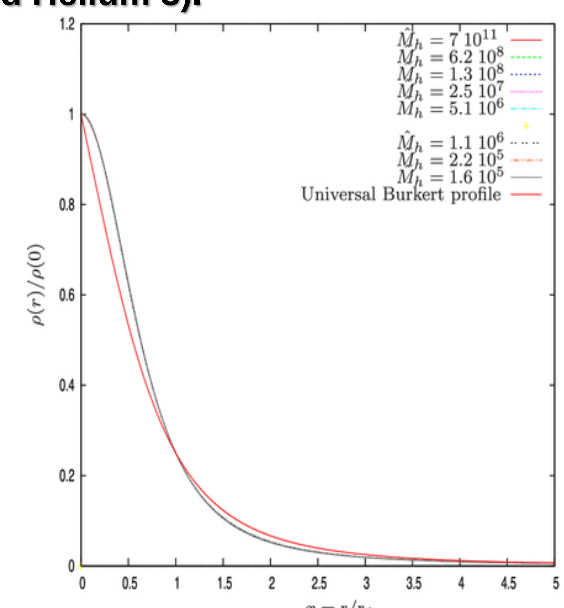
H.J. de Vega; P. Salucci; N. G.Sanchez MNRAS 442 (2): 2717-2727 (2014)

Newton, Fermi and Dirac, meet together in Galaxies through keV Warm Dark Matter

Rotation curves (left panel): The theoretical curves for 10 different galaxy masses all fall one into each other providing an Universal Rotation Curve (URC) which remarkably coincides with the observed universal curve (displayed in red) . Small deviations show up only at distances outside twice the *radius.*

The right panel the density profiles for the 10 galaxy masses: All fall into the same and universal density profile which reproduces the observed universal density profile and its size (in red). Interestingly enough, small deviations show up for compact dwarf galaxies as a manifestation of the quantum macroscopic effects predicted in these galaxies, and which can be further tested observations. (Examples of other macroscopic objects in nature are dwarf stars, neutron stars and the liquid Helium 3).





The equation of state of galaxies

We have derived the equation of state of galaxies, that is the relation between pressure and density, and provided its analytic expression : Two regimes for galaxies emerge : $P(r) = v^2(r)\ \rho(r)$

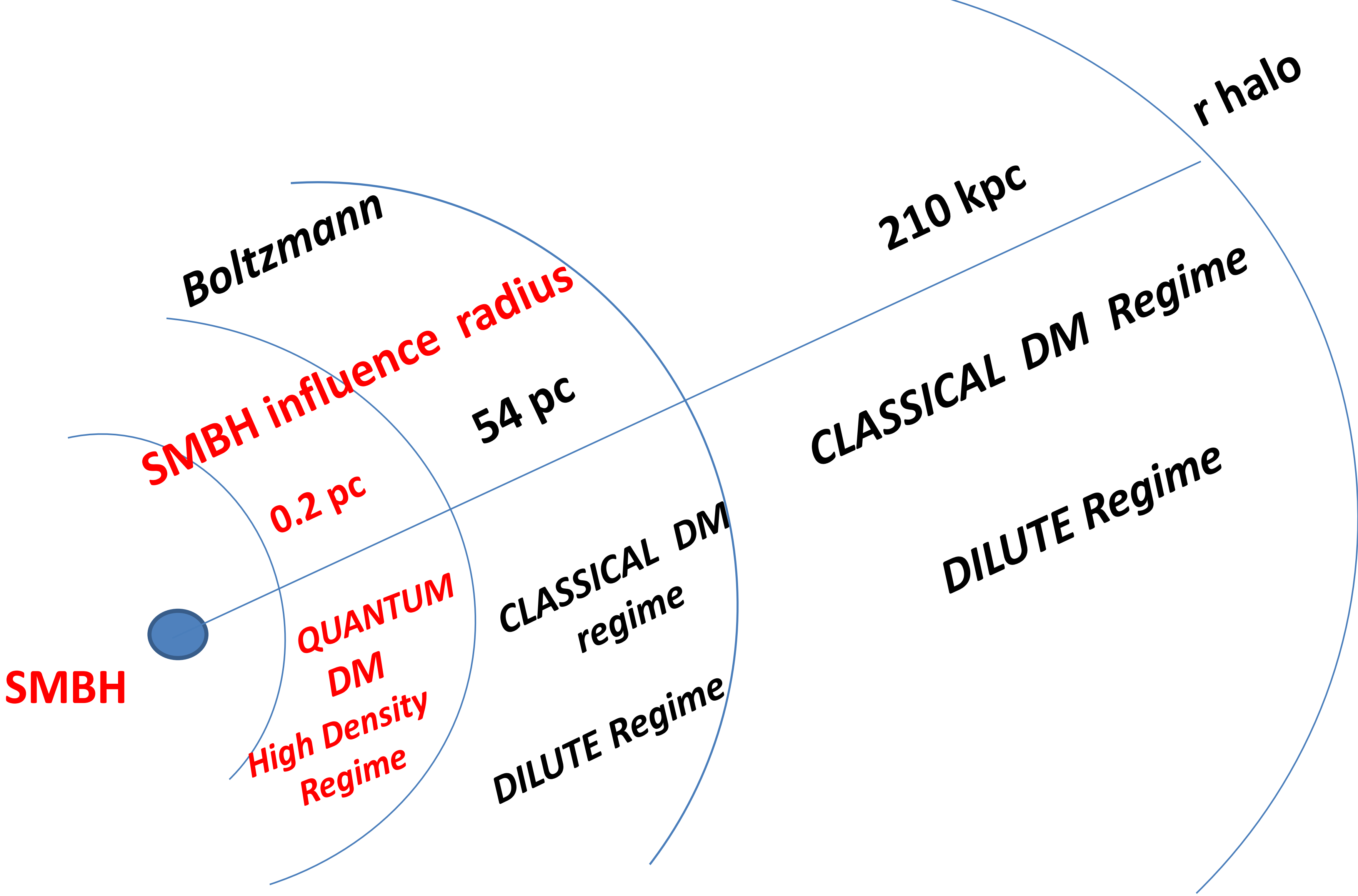
→(i) Large dilute galaxies for $M_h > 2{,}3\ 10^6$ Msun and effective températures $T_0 > 0{,}017$ K described by the classical Boltzmann gaz self-gravitational with local ideal gaz equation of state at each point (r-dependent).

→(ii) Compact dwarf galaxies for $1{,}6\ 10^6\ M_{sun} > M_h > M_{h,\,min} = 30000\ (2keV / m)^{16/5}\ M_{sun}$, $T_0 < 0{,}011$ K described by the fermion WDM quantum regime with an equation of state more steep near (but not at) the degenerate state. In particular, the degenerated limit T_0 = or extreme quantum limit yields the more compact and smallest galaxy. Moreover, in the dilute regime: the halo radius r_h , the v^2 and the temperature T_0 show scaling laws in terms of M_h. The amplitudes of these analytic scaling laws have been computed too.

→ **The normalized density and velocity profiles are universal fonctions of r / r_h. Thus, the scaling laws and the universality appearing in the dilute classical regime of large galaxies are linked to the ideal gaz behaviour of WDM in this regime.**

→ **These results and the theoretical rotation curves remarquably reproduce for r < r_h the galaxy observations.**

→ **In the compact regime of small galaxies: The equation of state depends on the mass of each galaxy: The density and velocity profiles are not anymore universal , this reflects the quantum physics of the WDM fermions in the compact regime (which generically are near but not at exactly the degenerate limit-state).**



WDM Thomas-Fermi Galaxy Theory with SMBH

SMBH: Super Massive Black holes

H.J. de Vega & N.G. Sanchez

The Distribution Function of Dark Matter

→ We developped inverse methods allowing to determine the distribution function f(E) from the real density profiles obtained from observations or from numerical simulations:

→ Thus, we have found the distribution function f (E) of galaxy DM halos and the corresponding equation of state from the DM observed density profiles .

→ That is to say, we have solved for galaxies the analogue of the integral Eddington equation of the gaz of stars in globular clusters . The observed density profiles are a realistic starting point, thus the f(E) obtained from them are realistic fonctions .

MORE RESULTS

→(i) CORED density profiles $\rho(r) \to \rho(0) - Kr^2$ produce distribution functions which are finite and positives at the center , while cusped density profiles with "cusps" growing as 1/r or more, always produce distribution functions which are divergent at the center.

→ (ii) The observed CORED density profiles produce distribution functions which are very near the THERMAL Boltzmann distributions for $r < 3rh$. (r_h being the halo radius).

→ (iii) The analytic expresions for the dispersion velocity and the pressure are derived, they verify the ideal gaz equation of state for the DM with a local temperature $T(r) = mv^2(r) / 3$.

T (r) is slowly variable and turns out to be constant in the same region where the distribution function is thermal.

→ **(iv) The DM halos can be consistently considered as being in Local Thermal Equilibrium with a temperature**

$T(r) = T_0$ **constant for** $r < 3\, r_h$,

and $T(r) = m\, v^2(r) / 3$

for $3\, r_h < r < R_{virial}$,

which slowly decreases with r.

That is to say, for $r < R_{virial}$,

the DM halo is a Self-Gravitant Thermal Gaz without collisions.

→ **(v) In the external halo region T(r) follows nicely the decreasing of the squared circular velocity**

The DM in the halos of galaxies is thermalized

- All these results show robustly that the DM self-gravitating gaz can thermalize in despite of being collissionless:
- This is due to the gravitational interaction between the DM particles and to the fact that this is an ergodic system.
- The collisionless self-gravitating gas is an isolated system which is not integrable.
- Namely, the particle trajectories explore ergodically the constant energy manifold in phase-space, covering it uniformly according to precisely the microcanonical measure and yielding to a thermal situation

- **Physically, these phenomena are clearly understood :**

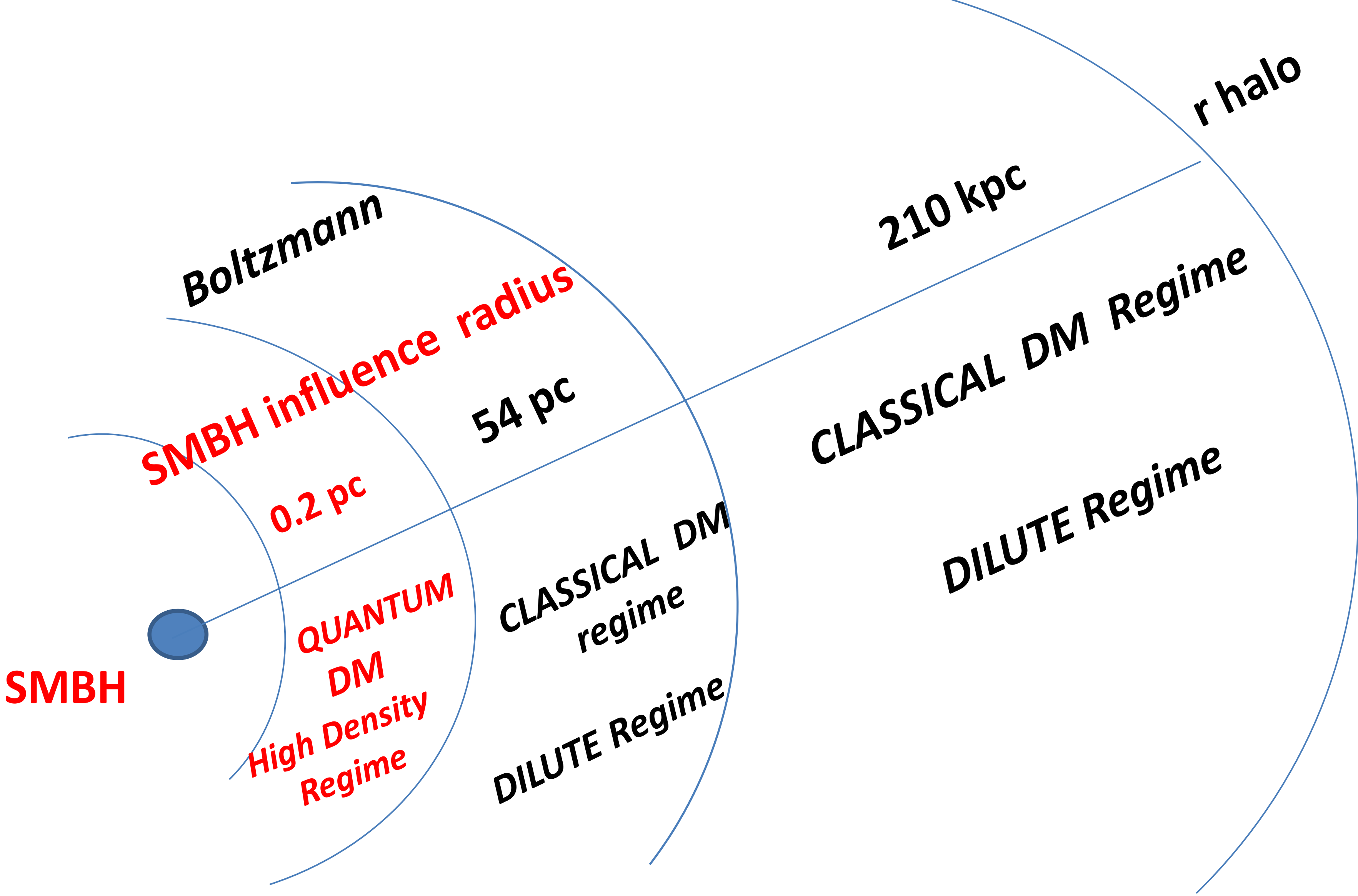
- **In the inner halo region the density is higher than beyond the halo radius.**

  The gravitational interaction in the inner region is strong enough and thermalizes the self-gravitating gas of DM particles,

  while beyond the halo radius the particles are too dilute to thermalize, namely, although they are virialized, they had not enough time to accomplish thermalization.

The DM in the galaxy halos is thermalized II

- Virialization always starts before than thermalization.
- In the process of thermalization there is an energy transfer flow of potential energy into kinetic energy.
- Clearly, in the outside halo region we find that the kinetic energy is lower than in the inside the region thermalization is already achieved.
- And All these results are consistent with the result found : The local temperature T(r) in the outside halo region is lower than the temperature inside the halo region where thermalisation is achieved.



WDM Thomas-Fermi Galaxy Theory with SMBH

SMBH: Super Massive Black holes

H.J. de Vega & N.G. Sanchez

THANK YOU

FOR YOUR ATTENTION