LWDM. Warm Dark Matter Galaxies in Agreement with Observations.

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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 in an 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

CONTENTS

(I) The Standard Model of the Universe Includes Inflation

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

(III) NEW: 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

HIGHLIGHTS

(I)The Effective (Ginsburg-Landau) Theory of Inflation

PREDICTIONS :

The Primordial Cosmic Banana: non-zero amount of primordial gravitons. And Forecasts for CMB exps.

(II) : TURNING POINT IN THE DARK MATTER PROBLEM: DARK MATTER IN GALAXIES from Theory and Observations: Warm (keV scale) dark matter

Physical Clarification and Simplification

GALAXY FORMATION AND EVOLUTION IN AGREEMENT WITH OBSERVATIONS

naturally re-insert in COSMOLOGY (LWDM)

Analytical Results and Numerical

NEW RESULTS

FERMIONIC QUANTUM WDM and GRAVITATION DETERMINE THE OBSERVED PHYSICAL GALAXY PROPERTIES

-> 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.

-> Recent study : Destri, de Vega, Sanchez, (New Astronomy 22, 39, 2013, Astrop.Phys 46,14 2013) suggest 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 with results 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) 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.

(iii) 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.

Standard Cosmological Model: ΛCDM $\Rightarrow$ ΛWDM

Dark Matter + Λ + Baryons + Radiation
begins by the Inflationary Era. Explains the Observations:

- Seven years WMAP data and further CMB data
- Light Elements Abundances
- Large Scale Structures (LSS) Observations. BAO.
- Acceleration of the Universe expansion: Supernova Luminosity/Distance and Radio Galaxies.
- Gravitational Lensing Observations
- Lyman α Forest Observations
- Hubble Constant and Age of the Universe Measurements
- Properties of Clusters of Galaxies
- Galaxy structure explained by WDM

From WMAP9 to Planck

Understanding the direction in which data are pointing:

- OUR PREDICTIONS for Planck
- Standard Model of the Universe
- Standard Single field Inflation
- NEGLIGEABLE RUNNING of the Primordial Spectral Index
- NEGLIGEABLE Primordial NON GAUSSIANITY
- N_{eff} neutrinos : --> Besides meV active neutrinos:
- 1 or 2 eV sterile neutrinos
- Would opens the sterile neutrino Family:
- keV sterile neutrino –WDM-

Sterile Neutrinos ν

Rhenium and Tritium beta decay (MARE, KATRIN).
Theoretical analysis: H J de V, O. Moreno, E. Moya de Guerra, M. Ramón Medrano, N. Sánchez,
Nucl. Phys. B866, 177 (2013).

[Other possibility to detect a sterile ν_s: a precise measure of nucleus recoil in tritium beta decay.]

Conclusion: the empty slot of right-handed neutrinos in the Standard Model of particle physics can be filled by keV-scale sterile neutrinos describing the DM.

An appealing mass neutrino hierarchy appears:

- Active neutrino: $\sim$ mili eV
- Light sterile neutrino: $\sim$ eV
- Dark Matter: $\sim$ keV
- Unstable sterile neutrino: $\sim$ MeV....

Sterile neutrinos and CMB fluctuations

CMB data give the effective number of neutrinos, $N_{\rm eff}$.
$N_{\rm eff}$ is related in a subtle way to the number of active neutrinos (3) plus the number of sterile neutrinos.
Planck result: $N_{\rm eff} = 3.5 \pm 0.5$ (95%;P+WP+highL+H_0+BAO)

Entropy conservation determines the contributions to $N_{\rm eff}$.
WDM sterile neutrino contribution at recombination
$\Delta N^{WDM} = \left(\frac{T_d}{T_{rc}}\right)^4 = \left[\frac{g_{rc}}{g(T_d)}\right]^{4/3}$. At recombination $g_{rc} = 29/4$.
WDM decouples early at T_d beyond the Fermi scale
The number of UR degrees of freedom at decoupling $g(T_d)$ includes all SM particles and probably beyond.
$g_{SM} = 427/4 \quad , \quad g_{MSSM} = 915/4$,
$\Delta N^{WDM}_{SM} = 0.02771\ldots \quad , \quad \Delta N^{WDM}_{MSSM} = 0.01003\ldots$
Too small to be measurable at present !
Planck results cannot provide information about WDM.
Besides, Planck results are **compatible** with one or two eV sterile neutrinos (see e. g. G. Steigman, 1303.0049).

Effective Theory of Inflation: Ginsburg-Landau Approach

Universal form of the slow-roll inflaton potential:

$V(\phi) = N\, M^4\, w\left(\frac{\phi}{\sqrt{N}\, M_{Pl}}\right)$, $N \sim 60$, $\phi =$ inflaton field.

$n_s - 1,\ r =$ order $\frac{1}{N}$. Running $\frac{dn_s}{d\ln k} \sim \frac{1}{N^2}$.

Primordial Non-Gaussianity $f_{NL} \sim \frac{1}{N}$.

Predictions combining with WMAP+LSS data:

$M = 0.70 \times 10^{16}$ GeV, = energy scale of inflation.

MCMC analysis calls for $w''(\chi) < 0$ at horizon exit
$\Longrightarrow$ double well potential favoured.

$$w(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$$

Bounds : $r > 0.023\ (95\%\ \mathrm{CL})$, $r > 0.046\ (68\%\ \mathrm{CL})$

Most probable values: $r \simeq 0.051 \Leftarrow$ measurable by Planck?

quartic coupling $y \simeq 1.26\ldots$ (moderate nonlinearity).

spectral index n_s, the ratio r and the running of n_s

$r \equiv$ ratio of tensor to scalar fluctuations.
tensor fluctuations = primordial gravitons.

$$n_s - 1 = -\frac{3}{N}\left[\frac{w'(\chi)}{w(\chi)}\right]^2 + \frac{2}{N}\,\frac{w''(\chi)}{w(\chi)} \quad , \quad r = \frac{8}{N}\left[\frac{w'(\chi)}{w(\chi)}\right]^2$$

$$\frac{dn_s}{d\ln k} = -\frac{2}{N^2}\,\frac{w'(\chi)\,w'''(\chi)}{w^2(\chi)} - \frac{6}{N^2}\,\frac{[w'(\chi)]^4}{w^4(\chi)} + \frac{8}{N^2}\,\frac{[w'(\chi)]^2\,w''(\chi)}{w^3(\chi)}$$

χ is the inflaton field at horizon exit.

$n_s - 1$ and r are always of order $1/N \sim 0.02$ (model indep.)

Running of n_s of order $1/N^2 \sim 0.0003$ (model independent).

Primordial Non-gaussianity $f_{NL} =$ order $1/N$

D. Boyanovsky, H. J. de Vega, N. G. Sanchez,
Phys. Rev. D 73, 023008 (2006), astro-ph/0507595.

Effective Theory of Inflation (ETI) confirmed by Planck

Quantity	ETI Prediction	Planck 2013
Spectral index $1 - n_s$	order $1/N = 0.02$	0.04
Running $dn_s/dlnk$	order $1/N^2 = 0.0004$	< 0.01
Non-Gaussianity f_{NL}	order $1/N = 0.02$	< 6
	ETI + WMAP+LSS	
tensor/scalar ratio r	r = 0.04-0.05	< 0.11
inflaton potential curvature $V''(0)$	$V''(0) < 0$	$V''(0) < 0$

ETI + WMAP+LSS means the MCMC analysis combining the ETI with WMAP and LSS data. Such analysis calls for an inflaton potential with negative curvature at horizon exit. The double well potential is favoured (new inflation). D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:0901.0549, IJMPA 24, 3669-3864 (2009).

Two key Observable numbers :

associated to the primordial density and Primordial Gravitons :

$n_s = 0.9608$, r

PREDICTIONS

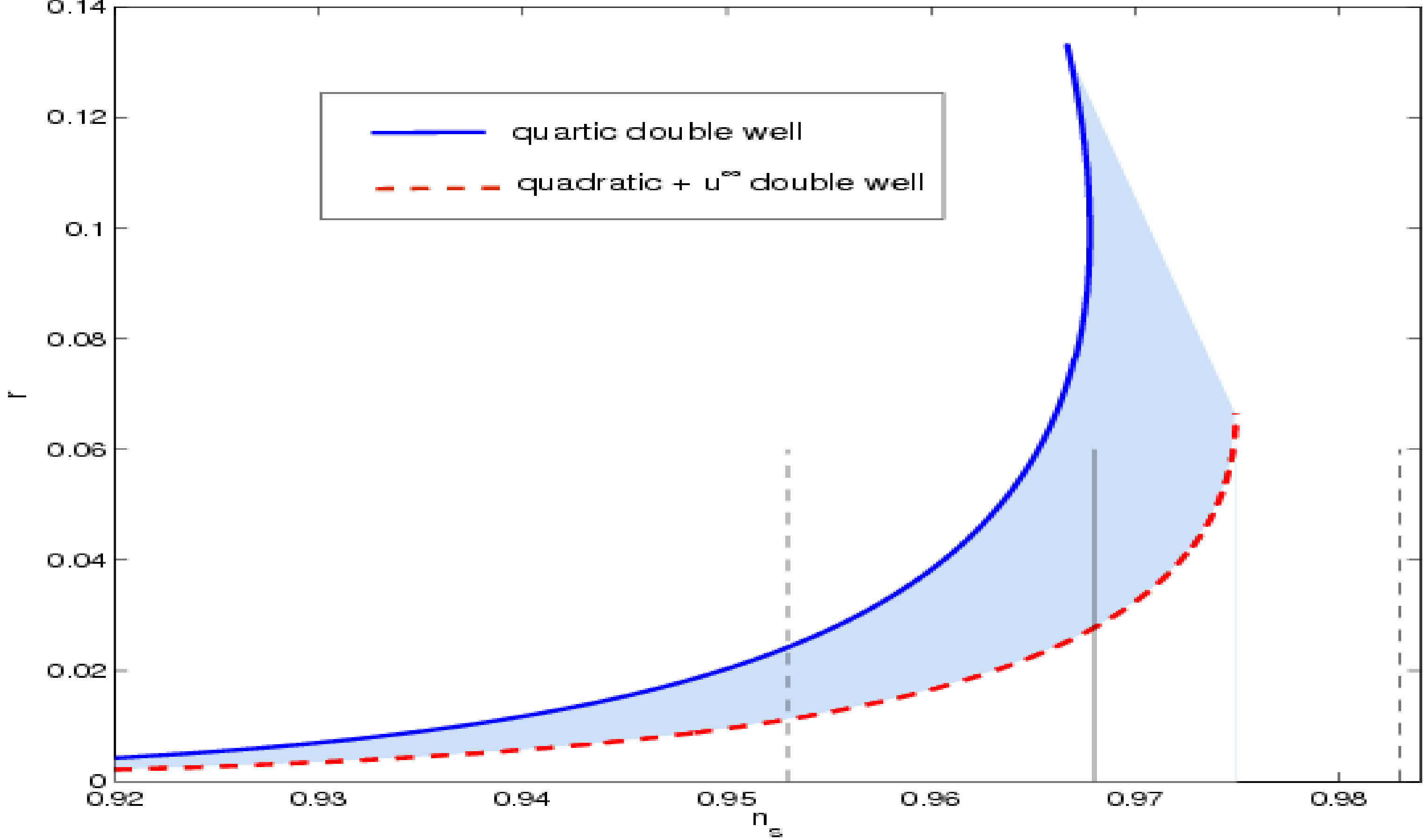
$r < 0.051$

Lower bound $r > 0.021$ NEW

$$0.021 < r < 0.053$$

Most probable value: $r \sim 0.04 - 0.05$

n_s max = 0.9678....NEW



THE PRIMORDIAL COSMIC BANANA

The tensor to scalar ratio r (primordial gravitons) versus the scalar spectral index n_s. The amount of r is always non zero
H.J. de Vega, C. Destri, N.G. Sanchez, Annals Phys 326, 578(2011)

• Large Hadron Collider

- **The first LHC results at 7-8 TeV, with the discovery of a candidate Higgs boson and the non observation of new particles or exotic phenomena, have made a big step towards completing the experimental confirmation of the Standard Model of particle physics.**

- **It is thus a good moment to recall our scientific predictions made several years ago on this matter because they are of full actuality.**

Large Hadron Collider - LHC-

The results are completely in line with the Standard Model.

No evidence of SUSY at LHC

"*Supersymmetry may not be dead but these latest results have certainly put it into hospital.*"

(Prof Chris Parkes, spokesperson for the UK Participation in the LHCb experiment)

→Does Not support wimps -CDM-

(In agreement with all dedicated wimp experiments at work from more than 20 years which have not found any wimp's signal) **"So far researchers who are racing to find evidence of so called "new physics", ie non-standard models, have run into a series of dead ends".**

The Energy Scale of Inflation

Grand Unification Idea (GUT)

- Renormalization group running of electromagnetic, weak and strong couplings shows that they all meet at $E_{GUT} \simeq 2 \times 10^{16}$ GeV
- Neutrino masses are explained by the see-saw mechanism: $m_\nu \sim \frac{M^2_{\texttt{Fermi}}}{M_R}$ with $M_R \sim 10^{16}$ GeV.
- Inflation energy scale: $M \simeq 10^{16}$ GeV.

Conclusion: the GUT energy scale appears in at least three independent ways.

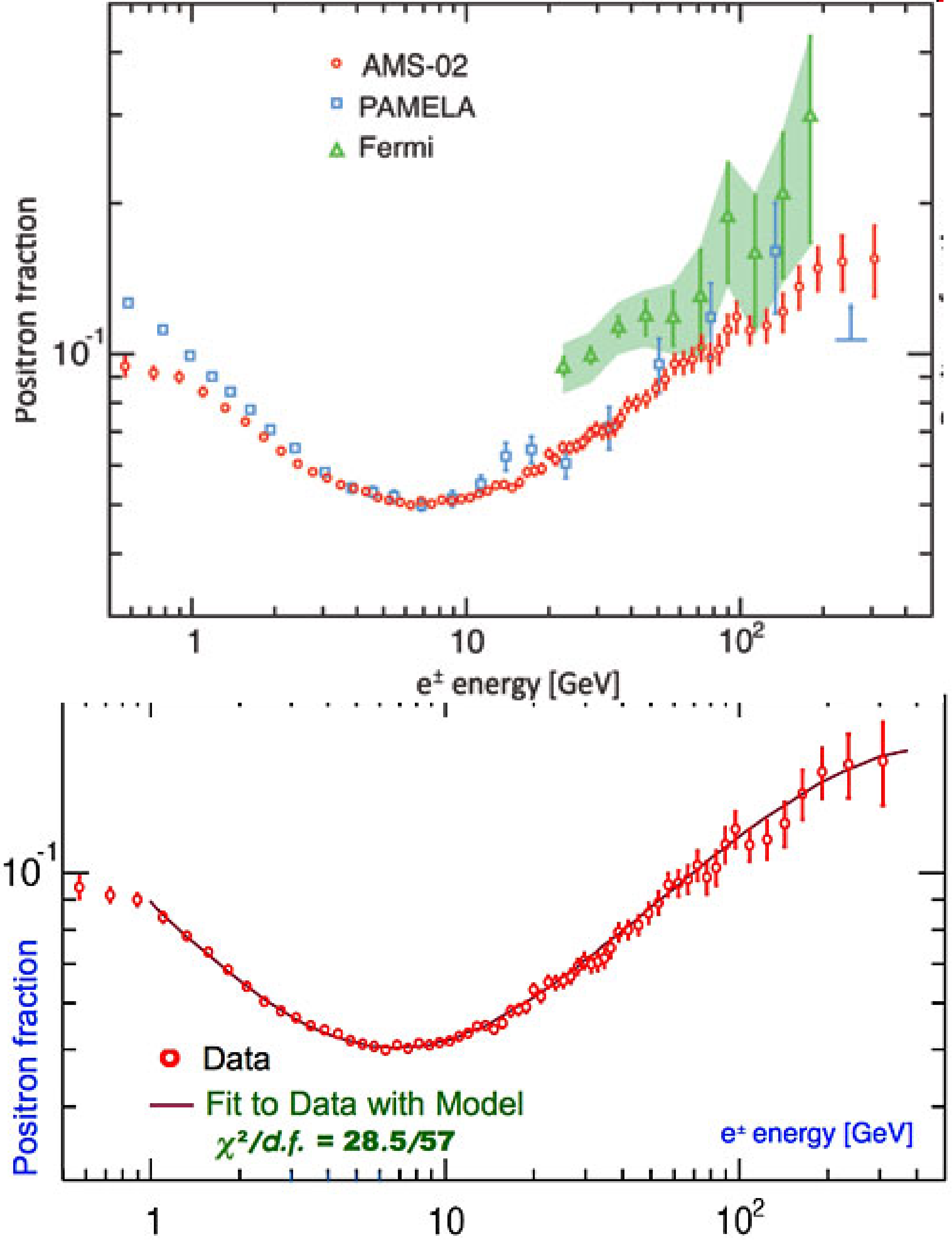
Moreover, moduli potentials: $V_{moduli} = M^4_{\text{SUSY}} \; v\left(\frac{\phi}{M_{Pl}}\right)$

ressemble inflation potentials provided $M_{\text{SUSY}} \sim 10^{16}$ GeV.

First observation of SUSY in nature??

ANTIMATTER IN SPACE - AMS on board ISS Alpha Magnet Spectrometer

NASA



Positron excess in cosmic rays are not related to DM physics but to astrophysical sources and astrophysical mechanisms and can be explained by them

LHC
AMS 2
PLANCK

Three beautiful and big experiments of performant instruments, technology, industry, achievements and successful operation which do not find the main scientific objective emphasized by them (or for which they were mainly designed)

Why No Experimental Detection of the DM particle has been reached so far ?

- **Because:**

- All experimental searches for DM particles are dedicated to CDM: wimps of m > 1 GeV,
- While the DM particle mass is in the keV scale .
- Moreover, past, present and future reports of signals of such CDM experiments **cannot be due to DM** because of the same reason.
- **The inconclusive signals in such experiments should be originated by phenomena of other kinds.**
- In addition, such signals contradict each other supporting the idea that they are **unrelated to any DM detection.**

Dark Matter Particles

DM particles decouple due to the universe expansion, their distribution function freezes out at decoupling.

The characteristic length scale is the free streaming scale (or Jeans' scale). For DM particles decoupling UR:

$r_{Jeans} = 57.2 \, \text{kpc} \, \frac{\text{keV}}{m} \left(\frac{100}{g_d}\right)^{\frac{1}{3}}$, solving the linear Boltz-V eqs.

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

DM particles can freely propagate over distances of the order of the free streaming scale.

Therefore, structures at scales smaller or of the order of r_{Jeans} are erased.

The size of the DM galaxy cores is in the ~ 50 kpc scale $\Rightarrow \; m$ should be in the keV scale (WDM particles).

For neutrinos $m \sim$ eV HDM particles
$r_{Jeans} \sim 60$ Mpc $\Rightarrow$ NO GALAXIES FORMED.

CDM free streaming scale

For CDM particles with $m \sim 100$ GeV: $r_{lin} \sim 0.1$ pc

Hence CDM structures keep forming till scales as small as the solar system.

This has been explicitly verified by all CDM simulations but never observed in the sky.

There is over abundance of small structures in CDM (also called the satellite problem).

Dark Matter: from primordial fluctuations to Galaxies

❖ **Cold (CDM): small velocity dispersion: small structures form first, bottom-up hierarchical growth formation, *too heavy (GeV)***

❖ **Hot (HDM) : large velocity dispersion: big structures form first, top-down, fragmentation, ruled out, *too light* (eV)**

Warm (WDM): ``in between”, *right mass scale,* (keV)

ΛWDM Concordance Model:

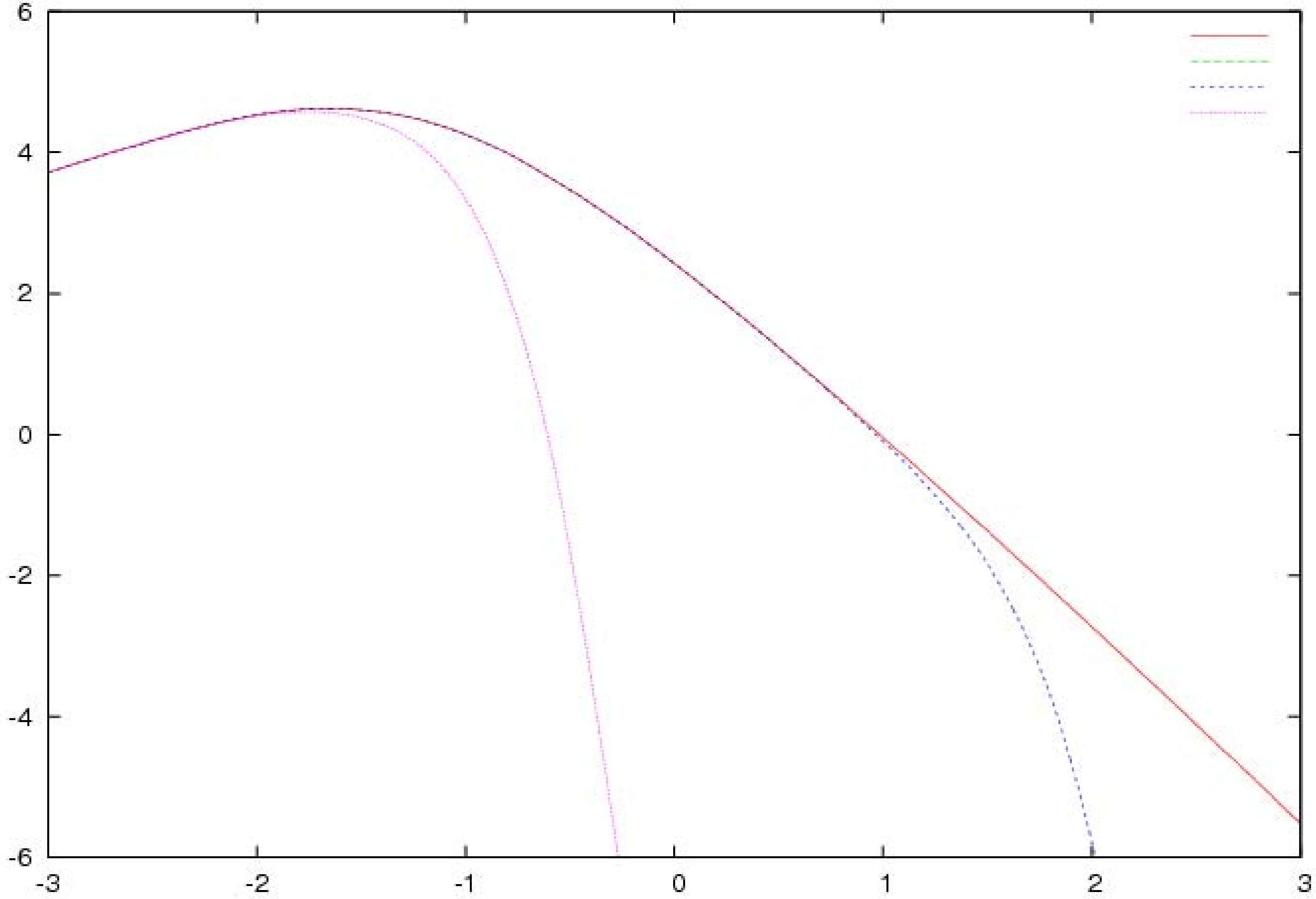
CMB + LSS + SSS Observations

DM is WARM and COLLISIONLESS

CDM Problems:

- ➢ **“clumpy halo problem”, large number of satellite galaxies**
- **“satellite problem”, overabundance of small structures**
- ➢ **ρ (r) ~ 1 / r (cusp)**
- ➢ **And other problems…..**

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

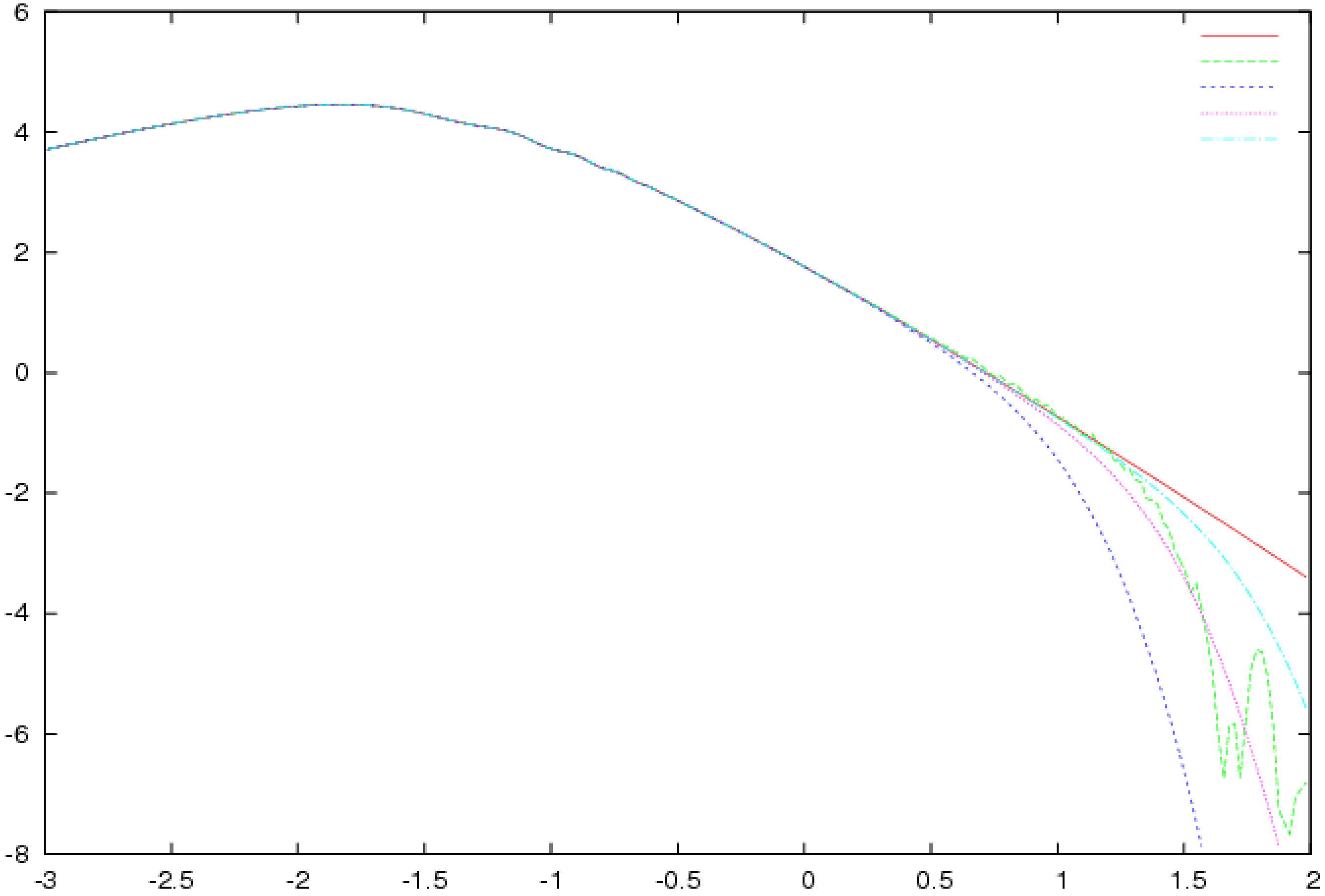


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS, 1 keV DM particles and 10 eV DM particles. $P(k) = P_0 \, k^{n_s} \, T^2(k)$.

$P(k)$ 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.

Sterile neutrino models

- DW: Dodelson-Widrow model (1994) sterile neutrinos produced by non-resonant mixing from active neutrinos.
- Shi-Fuller model (1998) sterile neutrinos produced by resonant mixing from active neutrinos.
- νMSM model (2005) sterile neutrinos produced by a Yukawa coupling from a real scalar χ.
- Models based on: Froggatt-Nielsen mechanism, flavor symmetries, see-saw mechanisms and several variations of it, left-right symmetries and others. Review by A Merle (2013).

WDM particles in the first 3 models behave primordially just as if their masses were different (FD = thermal fermions):

$\frac{m_{DW}}{\mathrm{keV}} \simeq 2.85\,(\frac{m_{FD}}{\mathrm{keV}})^{\frac{4}{3}},\; m_{SF} \simeq 2.55\,m_{FD},\; m_{\nu\mathrm{MSM}} \simeq 1.9\,m_{FD}$.

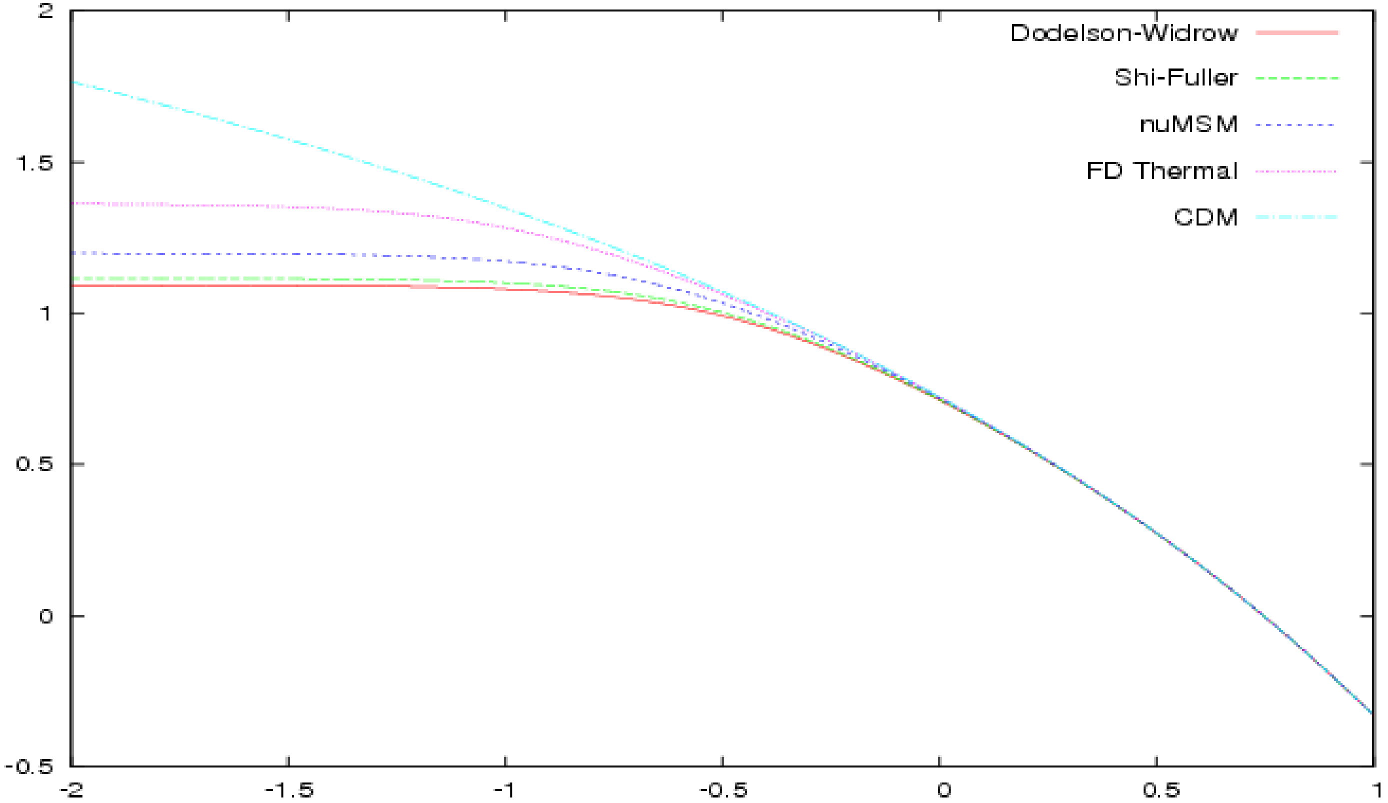
H J de Vega, N Sanchez, Warm Dark Matter cosmological fluctuations, Phys. Rev. D85, 043516 and 043517 (2012).

The expected overdensity

The expected overdensity within a comoving radius R in t

linear regime

$\sigma^2(R) = \int_0^\infty \frac{dk}{k}\, \Delta^2(k)\, W^2(kR) \quad , \quad W(kR)$: window functi



$\log_{10}\sigma^2(R, z=0)$ vs. $\log_{10}[R\, h/\mathrm{Mpc}]$ for $m = 2.5$ keV in fou

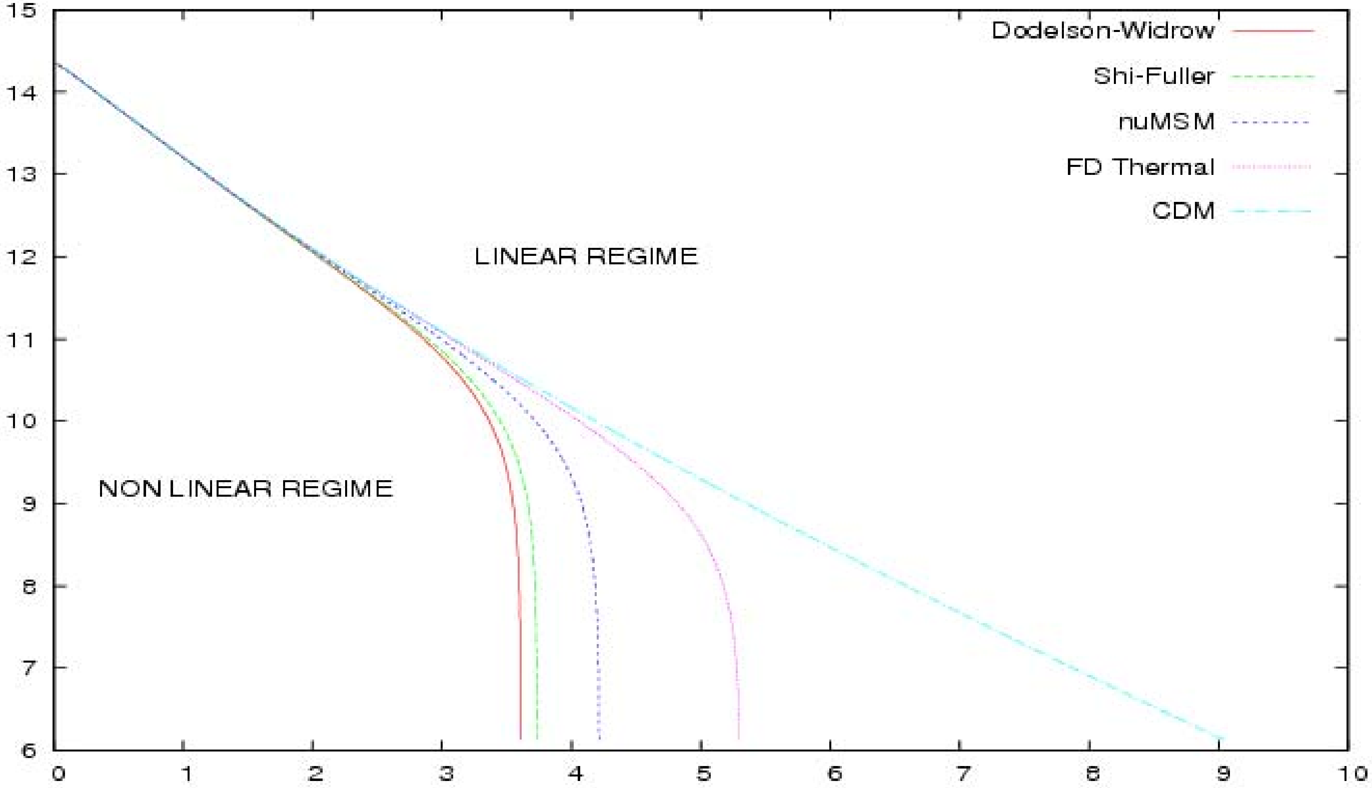
different WDM models and in CDM.

WDM flattens and reduces $\sigma(R)$ for small scales

Linear and non-linear regimes in z and R

$\sigma^2(R,z) \sim 1$: borderline between linear and non-linear regimes. Objects (galaxies) of scale R and mass $\sim R^3$ sta to form when this scale becomes non-linear.

Smaller objects can form earlier.



$\sigma^2(M,z) = 1$ in the z, $\log[h\ M/\mathrm{Mpc}]$ plane for $m = 2.5$ keV four different WDM models and in CDM

Relative overdensity D(R) and Press-Schechter approac

The differential mass function gives the number of isolated bounded structures with mass between M and $M + dM$: (Press-Schechter)

$$\frac{dN}{dM} = -\frac{2\,\delta_c}{\sqrt{2\,\pi}\,\sigma^2(M,z)}\,\frac{\rho_M(z)}{M^2}\,\frac{d\sigma(M,z)}{d\ln M}\,e^{-\delta_c^2/[2\,\sigma^2(M,z)]}\,,\quad \delta_c = 1.686\ldots$$

$\sigma(M, z)$ is constant for WDM for small scales: small objects formation is suppressed in WDM in comparison with CDM.

Computing dN/dM in WDM shows that small scale structure suppression with respect to CDM increases with z. It is therefore important to compare the observations at $z > 1$ with the theoretical predictions:

Menci et al. ApJ 2013, Nierenberg et al. ApJ 2013, Danese, de Vega, Lapi, Salucci, Sanchez (in preparation).

Conclusion: WDM reproduces the observed small scale structures better than CDM for redshifts up to eight where

WARM DARK MATTER REPRODUCE

→OBSERVED GALAXY DENSITIES AND VELOCITY DISPERSIONS

→SOLVES the OVERABUNDANCE (“satellite) PROBLEM

->OBSERVED SURFACE DENSITY VALUES OF DARK MATTER DOMINATED GALAXIES

→OBSERVED GALAXY CORED DENSITY PROFILES : QUANTUM MECHANICS

- OBSERVED GALAXY CORES vs CDM CUSPS and WDM CORES-

- **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.

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.**

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

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).

Quantum pressure vs. gravitational pressure

quantum pressure: $P_q =$ flux of momentum $= n\ v\ p$,

$v =$ mean velocity, momentum $= p \sim \hbar/\Delta x \sim \hbar\ n^{\frac{1}{3}}$,

particle number density $= n = \frac{M_q}{\frac{4}{3}\ \pi\ R_q^3\ m}$

galaxy mass $= M_q$, galaxy halo radius $= R_q$

gravitational pressure: $P_G = \frac{G\ M_q^2}{R_q^2} \times \frac{1}{4\,\pi\ R_q^2}$

Equilibrium: $P_q = P_G \Longrightarrow$

$$R_q = \frac{3^{\frac{5}{3}}}{(4\,\pi)^{\frac{2}{3}}}\ \frac{\hbar^2}{G\ m^{\frac{8}{3}}\ M_q^{\frac{1}{3}}} = 10.6\ldots\,\mathrm{pc}\left(\frac{10^6\ M_\odot}{M_q}\right)^{\frac{1}{3}}\ \left(\frac{\mathrm{keV}}{m}\right)^{\frac{8}{3}}$$

$$v = \left(\frac{4\,\pi}{81}\right)^{\frac{1}{3}}\ \frac{G}{\hbar}\ m^{\frac{4}{3}}\ M_q^{\frac{2}{3}} = 11.6\ \frac{\mathrm{km}}{\mathrm{s}}\ \left(\frac{\mathrm{keV}}{m}\right)^{\frac{4}{3}}\ \left(\frac{M_q}{10^6\ M_\odot}\right)^{\frac{2}{3}}$$

for WDM the values of $M_q,\ R_q$ and v are consistent with the dwarf galaxy observations !! .

Dwarf spheroidal galaxies can be supported by the fermionic quantum pressure of WDM.

Self-gravitating Fermions in the Thomas-Fermi appr

WDM is non-relativistic in the MD era. A single DM halo i
late stages of formation relaxes to a time-independent for
especially in the interior.

Chemical potential: $\mu(r) = \mu_0 - m\,\phi(r)\;,\;\; \phi(r) =$ grav. pot.

Poisson's equation: $\frac{d^2\mu}{dr^2} + \frac{2}{r}\,\frac{d\mu}{dr} = -4\,\pi\,G\,m\,\rho(r)$

$\rho(0) =$ finite for fermions $\Longrightarrow \frac{d\mu}{dr}(0) = 0$.

Density $\rho(r)$ and pressure $P(r)$ in terms of the distributio
function $f(E)$:

$$\rho(r) = \frac{m}{\pi^2\,\hbar^3} \int_0^\infty p^2\,dp\,f\left[\frac{p^2}{2\,m} - \mu(r)\right]$$

$$P(r) = \frac{m}{3\,\pi^2\,\hbar^3} \int_0^\infty p^4\,dp\,f\left[\frac{p^2}{2\,m} - \mu(r)\right]$$

Boundary condition at

$r = R = R_{200} \sim R_{vir}\;,\;\; \rho(R_{200}) \sim 200\,\bar{\rho}_{DM}$

we derive the local equation of state:

$$P(r) = \frac{1}{3} \, v^2(r) \, \rho(r) \quad .$$

) the hydrostatic equilibrium equation

$$\frac{dP}{dr} + \rho(r) \, \frac{d\phi}{dr} = 0 \, .$$

ion of state generalizes the local perfect fluid equation of state for r-dependent velocity $v(r)$.
e perfect fluid equation of state is recovered both in the classical dilute limit and in the quan

(r) between eqs.(2.6) and (2.7) and integrating on r gives

$$\frac{\rho(r)}{\rho(0)} = \frac{v^2(0)}{v^2(r)} \, e^{-3 \int_0^r \frac{dr'}{v^2(r')} \, \frac{d\phi}{dr'}} \quad .$$

) this relation reduces to the baryotropic equation. Inserting this expression for $\rho(r)$ in the Poiss

$$\frac{d^2\phi}{dr^2} + \frac{2}{r} \, \frac{d\phi}{dr} = 4\,\pi \, G \, m \, \rho(0) \, \frac{v^2(0)}{v^2(r)} \, e^{-3 \int_0^r \frac{dr'}{v^2(r')} \, \frac{d\phi}{dr'}} \quad .$$

quation generalizes the corresponding equation in the self-gravitating Boltzmann gas when $v^2($

RESULTS

All the obtained density profiles are cored.

The Core Sizes 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 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).

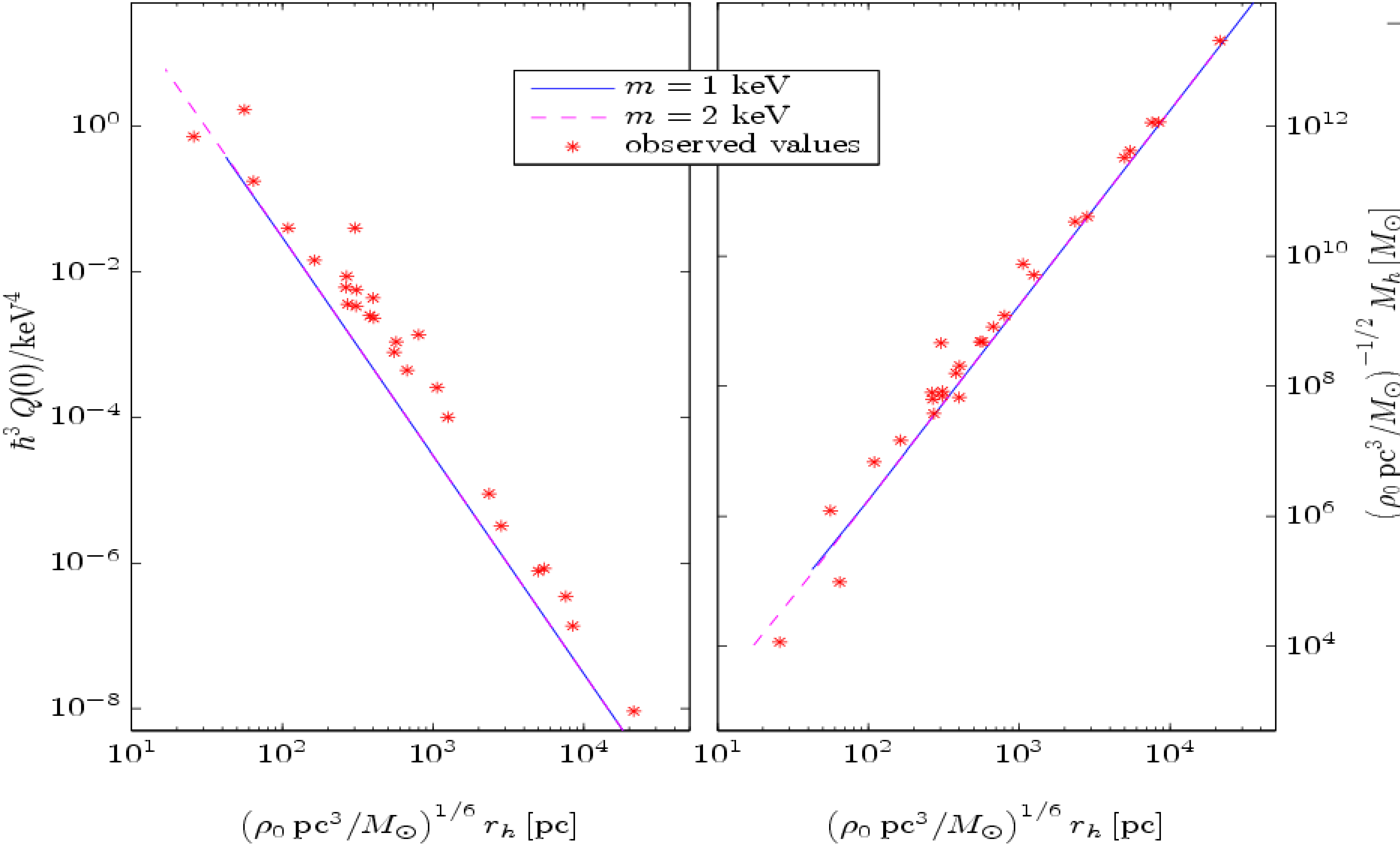
And

The Phase-space Density and The Galaxy halo Masses.

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 %.

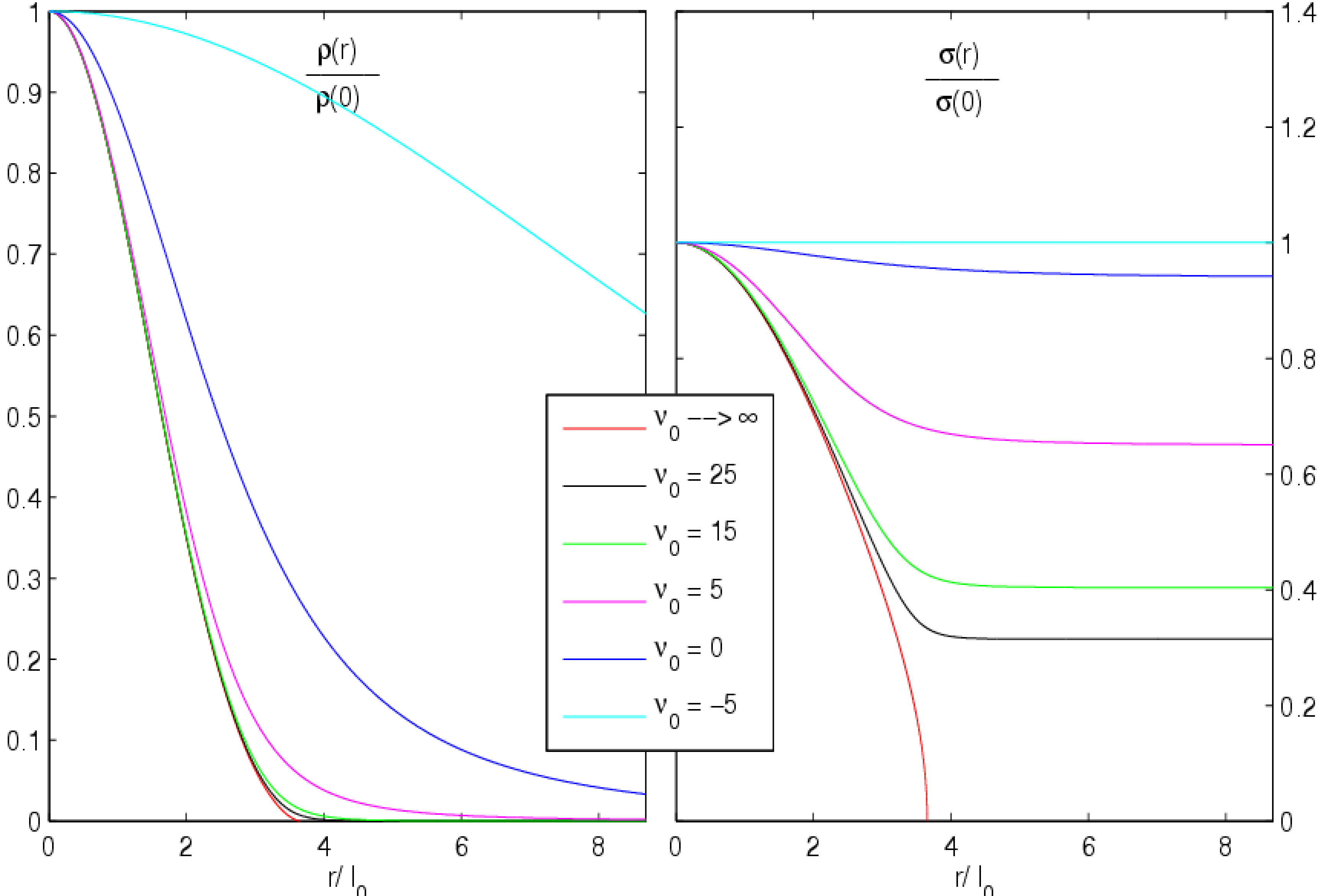
Q vs. halo radius. Galaxy observations vs. Thomas-Fermi



observed $Q = \rho/\sigma^3$ from stars are upper bounds for DM Q

Density and velocity profiles from Thomas-Fermi

Cored density profile and velocity profile obtained from Thomas-Fermi.



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

THE MINIMAL GALAXY MASS

A minimal galaxy mass and minimal velocity dispersion are found.

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 approximately around 2 keV-2.5 keV.

More precise data will make this estimation more precise.

Minimal galaxy mass from degenerate WDM

The halo radius, the velocity dispersion and the galaxy mass take their minimum values for degenerate WDM:

$$r_{h\ min} = 24.51\ldots \ \text{pc} \ \left(\frac{m}{\text{keV}}\right)^{\frac{4}{3}} \left[\rho(0) \ \frac{\text{pc}^3}{M_\odot}\right]^{\frac{1}{6}}$$

$$M_{min} = 2.939\ldots \ 10^5 \ M_\odot \ \left(\frac{\text{keV}}{m}\right)^4 \sqrt{\rho(0) \ \frac{\text{pc}^3}{M_\odot}}$$

$$\sigma_{min}(0) = 2.751\ldots \ \frac{\text{km}}{\text{s}} \ \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}} \left[\rho(0) \ \frac{\text{pc}^3}{M_\odot}\right]^{\frac{1}{3}} \ .$$

These minimum values correspond to the observations of compact dwarf galaxies.

Lightest known compact dwarf galaxy is Willman I:

$$M_{Willman\ I} = 2.9 \ 10^4 \ M_\odot$$

Imposing $M_{Willman\ I} > M_{min}$ yields the lower bound for the WDM particle mass: $m > 1.91$ keV.

• WDM OVERALL CONCLUSION

- To conclude, we find 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.

- The resulting galaxy, halo radius, galaxy masses and velocity dispersion are fully consistent with observations for all different types of galaxies. 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 > kpc.

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 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

END

THANK YOU FOR YOUR ATTENTION

Future Perspectives: Detection!

Sterile neutrino detection depends upon the particle physics model. There are sterile neutrino models where the keV sterile is stable and thus hard to detect.

Astronomical observation of steriles:
X-ray data from galaxy halos.

Direct detection of steriles in Lab:

Bounds on mixing angles from
Mare, Katrin, ECHo, Project 8 and PTOLEMY are expected.

For a particle detection a dedicated beta decay or electron capture experiment looks necessary to search sterile neutrinos with mass around 2 keV.

Calorimetric techniques seem well suited.

Best nuclei for study:

Electron capture in ^{163}Ho, beta decay in ^{187}Re and Tritium.

X-ray detection of DM sterile neutrinos

Sterile neutrinos ν_s decay into active neutrinos ν_e plus X-rays with a lifetime $\sim 10^{11}\times$ age of the universe.

These X-rays may be seen in the sky looking to galaxies ! recent review: C. R. Watson et al. JCAP, (2012).

Future observations:

- Satellite projects: Xenia (NASA), ASTRO-H (Japan).
- CMB: WDM decay distorts the blackbody CMB spectrum. The projected PIXIE satellite mission (A. Kogut et al.) can measure WDM sterile neutrino mass.
- PTOLEMY experiment: Princeton Tritium Observatory. Aims to detect the cosmic neutrino background and WDM (keV scale) sterile neutrinos through the electron spectrum of the Tritium beta decay induced by the capture of a cosmic neutrino or a WDM sterile neutrino.

Results from Supernovae: θ unconstrained $1 < m < 10$ keV