



*Warm Dark Matter Galaxy
Formation in Agreement with
Observations*

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[DARK MATTER : FACTS AND STATUS

→ DARK MATTER DOES EXIST

→ ASTROPHYSICAL OBSERVATIONS POINTS TO THE EXISTENCE OF DARK MATTER

→ AFTER MORE THAN TWENTY YEARS OF DEDICATED DARK MATTER PARTICLE EXPERIMENTS, THE DIRECT SEARCH OF DARK MATTER PARTICLES FULLY CONCENTRATED IN “GeV WIMPS” REVEALED SO FAR, UNSUCCESSFUL. **BUT DARK MATTER DOES EXIST**

IN DESPITE OF THAT: PROPOSALS TO REPLACE DARK MATTER DID APPEARED:

PROPOSING TO CHANGE THE LAWS OF PHYSICS (!!!), ADDING OVER CONFUSION,...

TODAY, THE DARK MATTER RESEARCH AND DIRECT SEARCH SEEMS TO SPLIT IN THREE SETS:

(1). PARTICLE PHYSICS DARK MATTER: PARTICLE BUILDING MODELS, DEDICATED LAB EXPERIMENTS, ANNIHILATING DARK MATTER, (FULLY CONCENTRATED ON “GeV WIMPS”)

(2). ASTROPHYSICAL DARK MATTER: (ASTROPHYSICAL MODELS, ASTROPHYSICAL OBSERVATIONS)

(3). NUMERICAL SIMULATIONS

(1) and (2) DO NOT AGREE IN THE RESULTS

and (2) and (3) DO NOT FULLY AGREE NEITHER

SOMETHING IS GOING WRONG IN THE RESEARCH ON THE DARK MATTER

WHAT IS GOING WRONG ?, [AND WHY IS GOING WRONG]

“THE ONLY ANSWER (“NO ONE BELIEVES THE EVIDENCE”) IS NOT

THE SUBJECT IS MATURE

- THERE EXIST ASTRONOMICAL OBSERVATIONS AND FACILITIES
- THERE EXIST MODEL /THEORETICAL ASTROPHYSICAL RESULTS WHICH FIT, AGREE WITH THE ASTRONOMICAL OBSERVATIONS
 - THERE EXISTED, THERE EXIST MANY DARK MATTER DEDICATED PARTICLE EXPERIMENTS (ALTHOUGH FULLY CONCENTRATED IN “GeV WIMPS”)
- THERE EXIST COMPUTER AND SUPER COMPUTERS AND DIFFERENT RESEARCHER GROUPS PERFORMING WORK WITH THEM
 - THERE EXIST A CONSIDERABLE AMOUNT OF RESEARCHERS WORKING IN DARK MATTER DURING MORE THAN TWENTY YEARS

**“ FUITE EN AVANT” (“ESCAPE TO THE FUTURE”) IS NOT THE ISSUE
WHAT IS WRONG in the present day subject of Dark Matter?
(The Answer is Trivial and can be found in these 3 slides)**

Basement-zeroth-floor

**Dark matter 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) dark matter

**(III) GALAXY DENSITY PROFILES, UNIVERSAL
GALAXY PROPERTIES and SURFACE DENSITY**

Analytical Results

and Numerical (including analytical) Results

Galaxy cores from Fermionic WDM

(IV) THE CASE FOR THE keV STERILE NEUTRINO

MASS OF THE DARK MATTER PARTICLE

H. J. De Vega, N.G. Sanchez *Model independent analysis of dark matter points to a particle mass at the keV scale* **Mon. Not. R. Astron. Soc. 404, 885 (2010)**

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)**

BOLTZMAN VLASOV EQUATION, TRANSFERT FUNCTION

D. Boyanovsky, H. J. de Vega, N.G. Sanchez *The dark matter transfer function: free streaming, particle statistics and memory of gravitational clustering* **Phys. Rev. D78: 063546, (2008)**

DENSITY PROFILES, SURFACE DENSITY, DARK MATTER PARTICLE MASS

H. J. de Vega, N.G. Sanchez *Gravity surface density and density profile of dark matter galaxies* **IJMPA26:1057 (2011)**

H. J. de Vega, P. Salucci, N.G. Sanchez *The mass of the dark matter particle from theory and observation* **New Astronomy, 17, 653 -666 (2012)**

Fermionic warm dark matter produces galaxy cores in the observed scales, C. Destri, H.J. de Vega, N. G. Sanchez , arXiv: 1204.3090

Search of Sterile Neutrino Warm Dark Matter in the Rhenium and Tritium beta decays, H.J. de Vega, O Moreno, E. Moya de Guerra, M. Ramon Medrano, N. G. Sanchez, arXiv:1109.3452

**Cosmological evolution of warm dark matter
fluctuations I:**

**Efficient computational framework with Volterra
integral equations**

**H.J. de Vega, N.G. Sanchez, *Phys. Rev. D*85,
043516 (2012)**

**Cosmological evolution of warm dark matter
fluctuations II:**

**Solution from small to large scales and keV sterile
neutrinos**

**H.J. de Vega, N.G. Sanchez, *Phys. Rev. D*85, 043517
(2012)**

Universe Inventory

The universe is spatially flat: $ds^2 = dt^2 - a^2(t) d\vec{x}^2$
plus small primordial fluctuations.

Dark Energy (Λ): 74 % , Dark Matter: 21 %

Baryons + electrons: 4.4 % , Radiation ($\gamma + \nu$): 0.0085%

83 % of the matter in the Universe is **DARK**.

$$\rho(\text{today}) = 0.974 \cdot 10^{-29} \frac{\text{g}}{\text{cm}^3} = 5.46 \frac{\text{GeV}}{\text{m}^3} = (2.36 \cdot 10^{-3} \text{ eV})^4$$

DM dominates in the **halos** of galaxies (external part).

Baryons dominate around the **center** of galaxies.

Galaxies form out of matter collapse. Since angular momentum is conserved, when matter collapses its velocity increases. If matter can lose energy radiating, it can fall deeper than if it cannot radiate.

Standard Cosmological Model: Λ CDM \Rightarrow Λ WDM

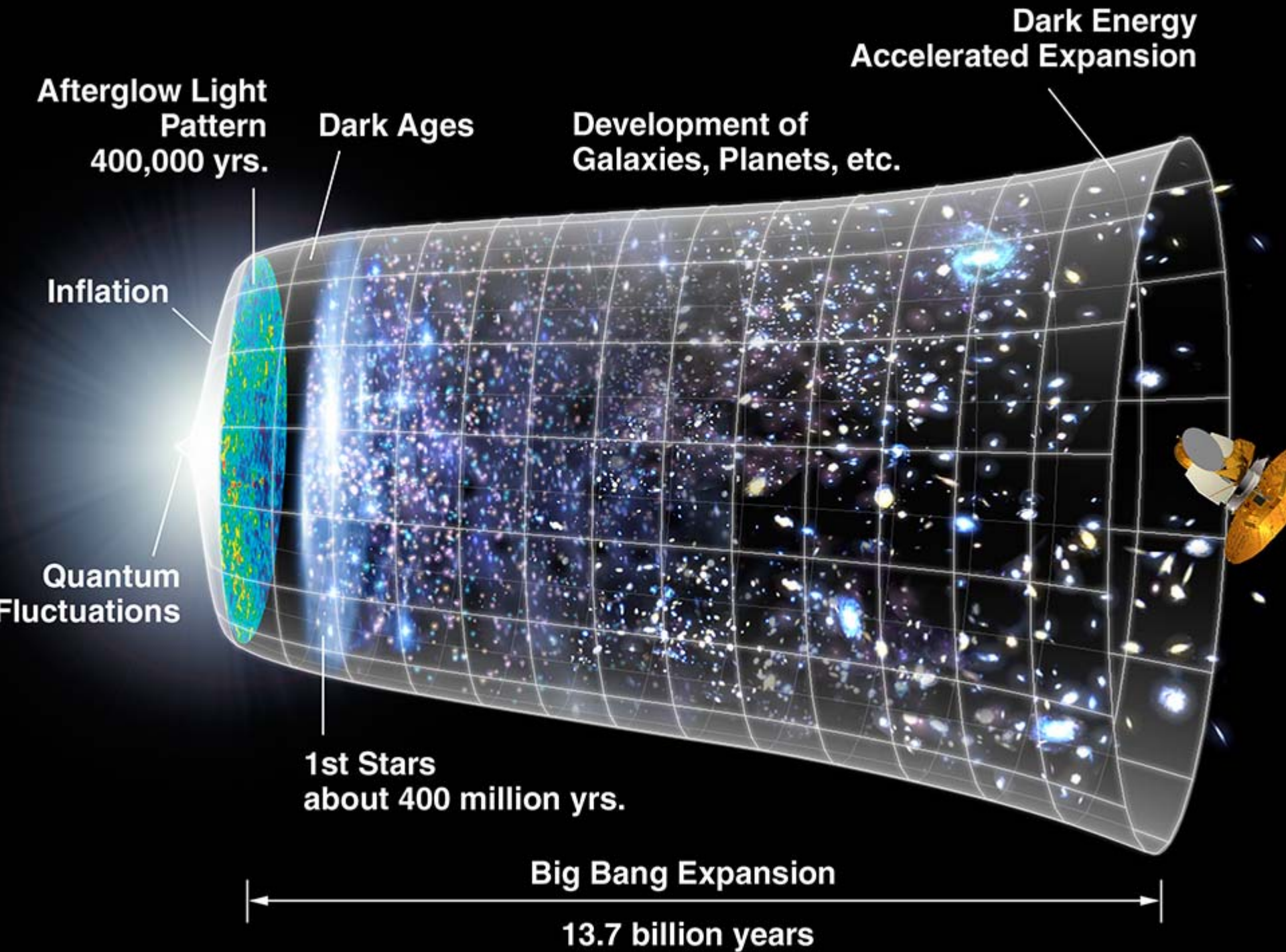
Dark Matter + Λ + Baryons + Radiation

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

Standard Cosmological Model: DM + Λ + Baryons + Radiation

- Begins by the **inflationary** era. Slow-Roll inflation explains horizon and flatness.
- Gravity is described by Einstein's General Relativity.
- Particle Physics described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model.
- Dark matter is non-relativistic during the matter dominated era where structure formation happens. DM is outside the SM of particle physics.
- Dark energy described by the cosmological constant Λ .



Quantum Fluctuations During Inflation and after

The Universe is homogeneous and isotropic after inflation thanks to the fast and **gigantic** expansion stretching lengths by a factor $e^{62} \simeq 10^{27}$. By the end of inflation: $T \sim 10^{14}$ GeV.

Quantum fluctuations around the classical inflaton and FRW geometry were of course **present**.

These inflationary quantum fluctuations are the **seeds** of the structure formation and of the CMB anisotropies today: galaxies, clusters, stars, planets, ...

That is, our present universe **was built** out of inflationary quantum fluctuations. CMB anisotropies spectrum:

$$3 \times 10^{-32} \text{cm} < \lambda_{\text{begin inflation}} < 3 \times 10^{-28} \text{cm}$$

$$M_{\text{Planck}} \gtrsim 10^{18} \text{ GeV} > \lambda_{\text{begin inflation}}^{-1} > 10^{14} \text{ GeV}.$$

total redshift since inflation begins till today = 10^{56} :

$$0.1 \text{ Mpc} < \lambda_{\text{today}} < 1 \text{ Gpc}, \quad 1 \text{ pc} = 3 \times 10^{18} \text{ cm} = 200000 \text{ AU}$$

Universe expansion classicalizes the physics: **decoherence**

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)*

Λ WDM 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
- $\rho(r) \sim 1/r$ (cusp)
- And other problems.....

Dark Matter Particles

DM particles can decouple being **ultrarelativistic** (UR) or non-relativistic.

They can decouple **at or out** of thermal equilibrium.

The DM distribution function **freezes out** at decoupling.

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

$$r_{lin} = 57.2 \text{ kpc} \frac{\text{keV}}{m} \left(\frac{100}{g_d} \right)^{\frac{1}{3}}$$

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

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

For $m \sim \text{keV}$ WDM particles $r_{lin} \sim 60 \text{ kpc}$, is the size of the DM cores.

The Free Streaming Scale

The characteristic length scale is the **free streaming scale** (or Jeans' scale)

$$r_{lin} = 2 \sqrt{1 + z_{eq}} \left(\frac{3 M_{Pl}^2}{H_0 \sqrt{\Omega_{DM}} Q_{prim}} \right)^{\frac{1}{3}} = 21.1 q_p^{-\frac{1}{3}} \text{ kpc}$$

$q_p \equiv Q_{prim}/(\text{keV})^4$. DM particles can **freely** propagate over distances of the order of the free streaming scale.

$$r_{lin} = 57.2 \text{ kpc} \frac{\text{keV}}{m} \left(\frac{100}{g_d} \right)^{\frac{1}{3}}$$

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

It is useful to introduce the dimensionless wavenumbers:

$$\gamma \equiv k r_{lin}/\sqrt{3} \quad \text{and} \quad \alpha \equiv \sqrt{3} \gamma/\sqrt{I_4}$$

where I_4 is the second momentum of the DM zeroth order distribution.

CDM free streaming scale

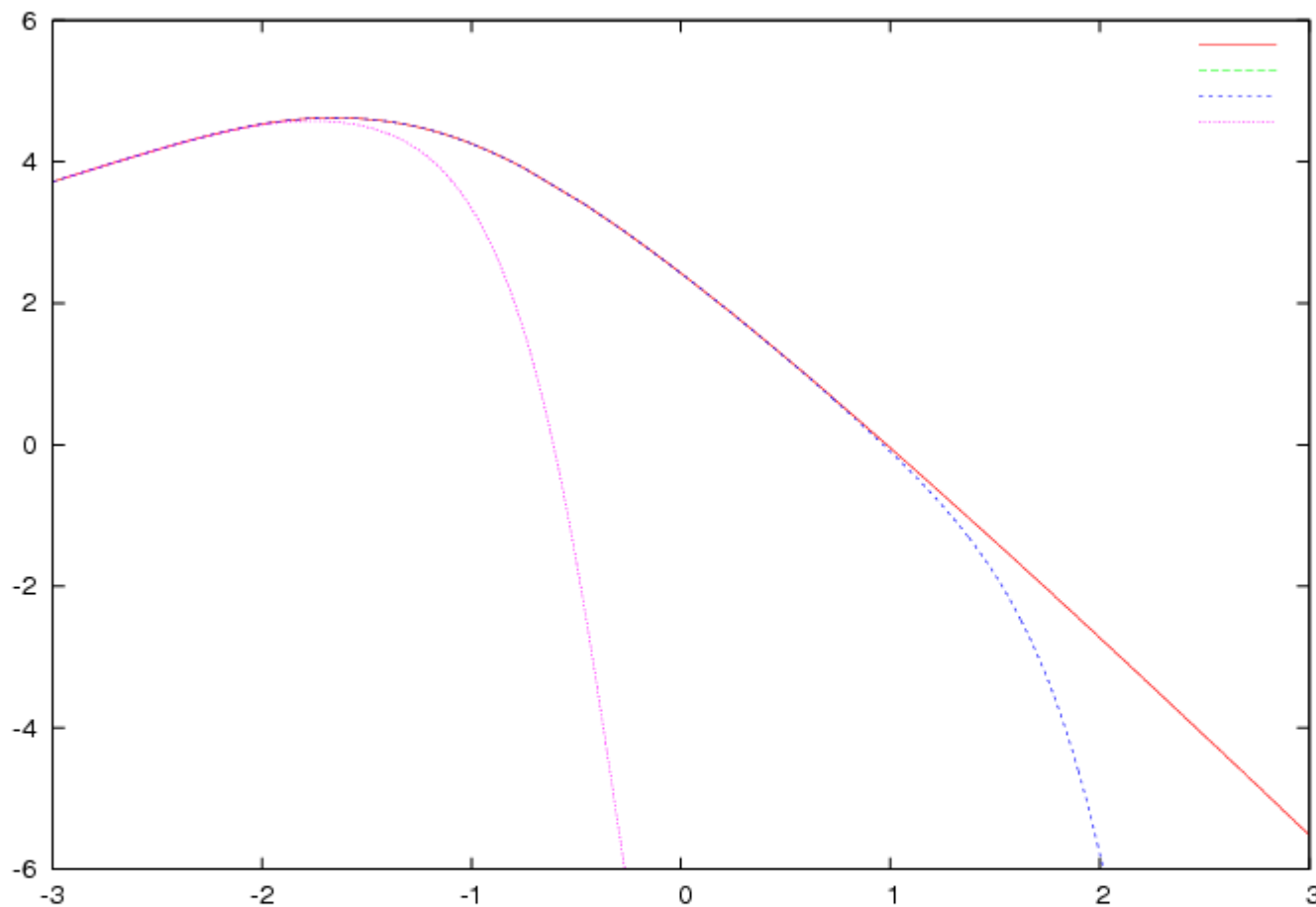
For CDM particles with $m \sim 100$ GeV: $r_{lin} \sim 0.1$ pc

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).

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

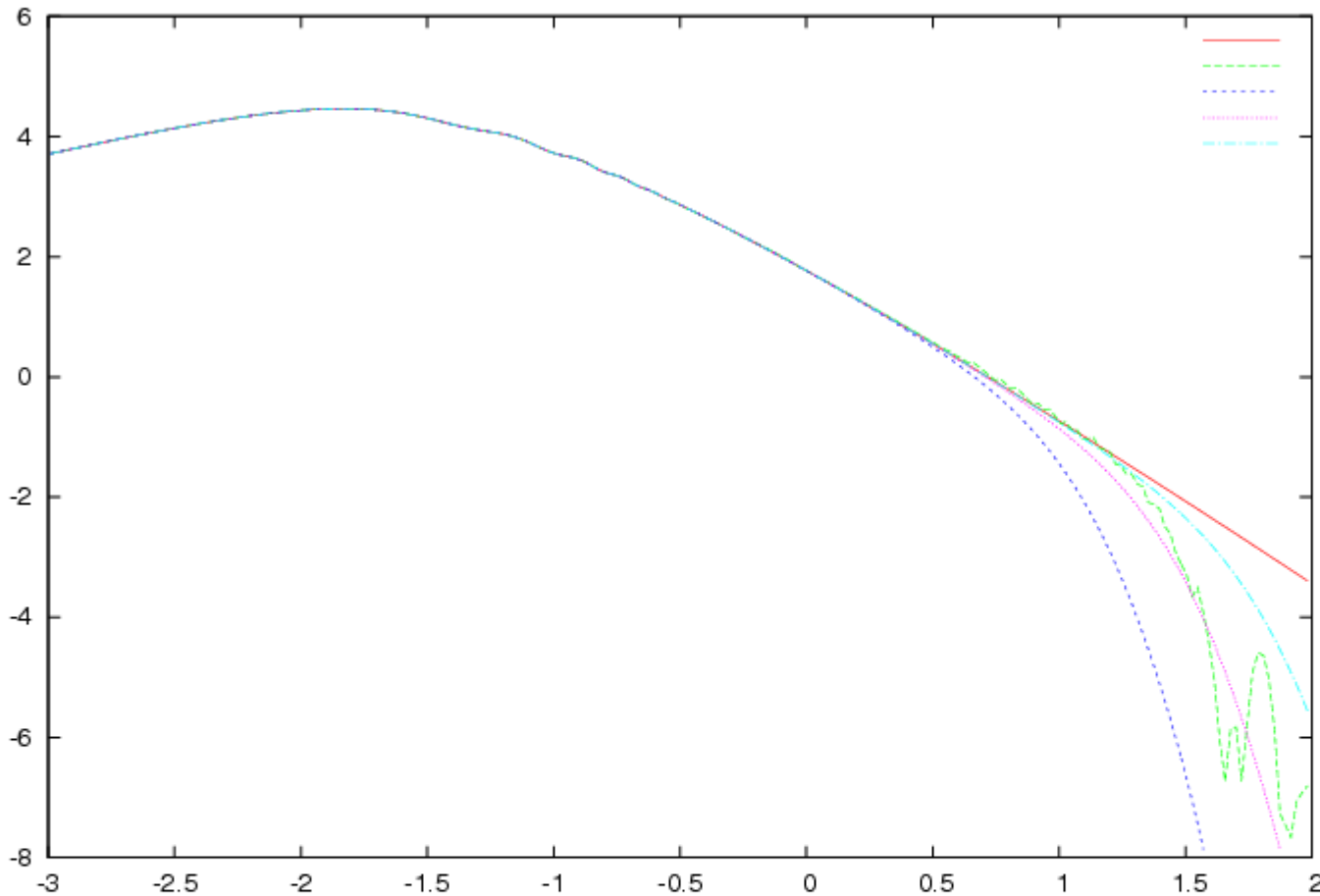


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for **WIMPS**, **1 keV** DM particles and **10 eV** DM particles. $P(k) = P_0 k^{n_s} T^2(k)$.

$P(k)$ 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



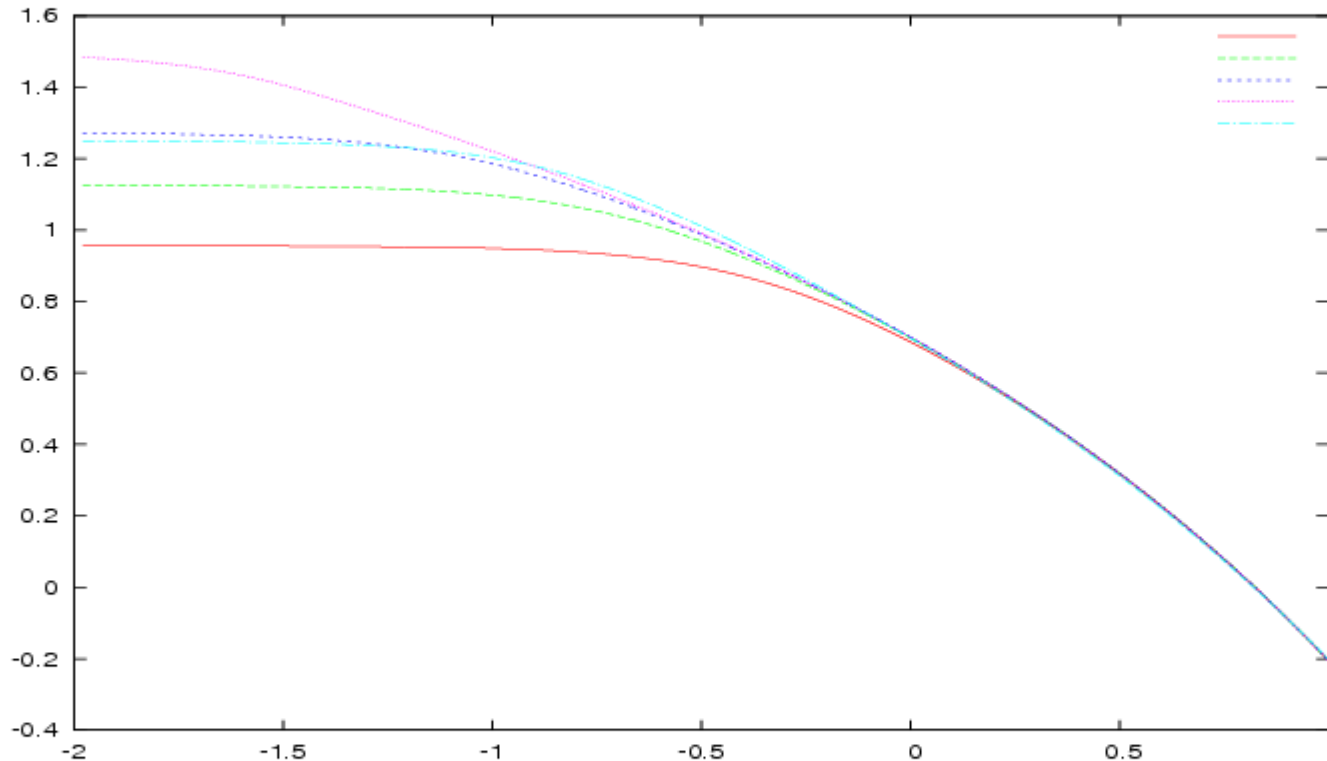
$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for **CDM**, **1 keV**, **2 keV**,
light-blue 4 keV DM particles decoupling in equil, and 1
keV **sterile neutrinos**. WDM cuts $P(k)$ on small scales

$$r \lesssim 100 (\text{keV}/m)^{4/3} \text{ kpc}$$

The expected overdensity

The expected overdensity within a radius R in the linear regime

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



$\log \sigma(R)$ vs. $\log R$ for CDM, 1 keV, 2 keV, 4 keV DM particles decoupling in equil, and 1 keV (light-blue) sterile neutrinos. WDM flattens and reduces $\sigma(R)$ for small scales.

The Mass function

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

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

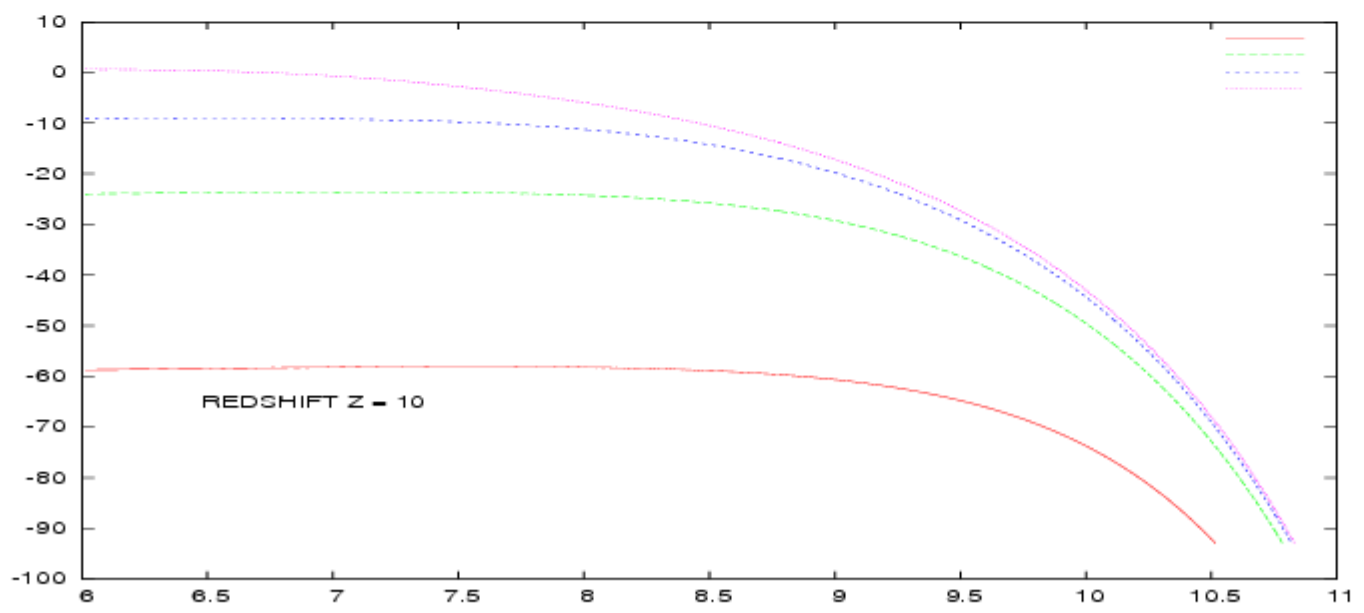
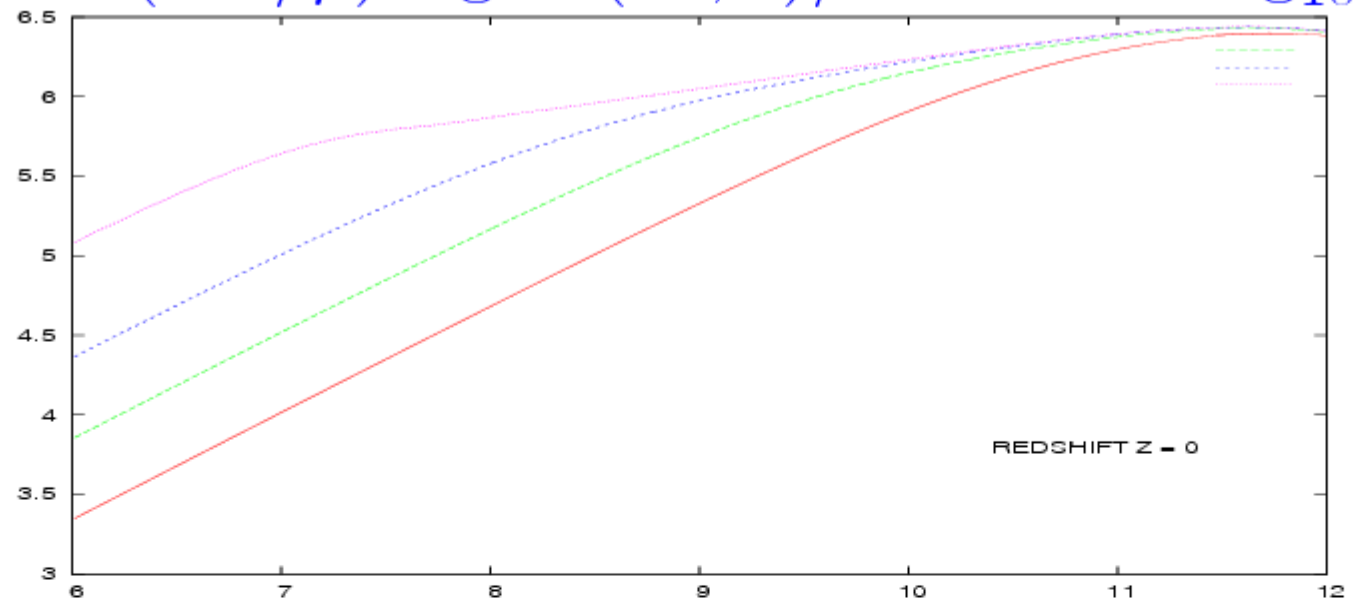
$\delta_c = 1.686 \dots$: linear estimate for collapse from the spherical model.

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

$$\sigma(M, z) = \frac{g(z)}{z+1} \sigma(M, 0)$$

$g(z)$: takes into account the effect of the cosmological constant, $g(0) = 0.76$, $g(\infty) = 1$

$(M^2/\rho) \log d\sigma(M, z)/d \ln M$ vs. $\log_{10} M/M_\odot$

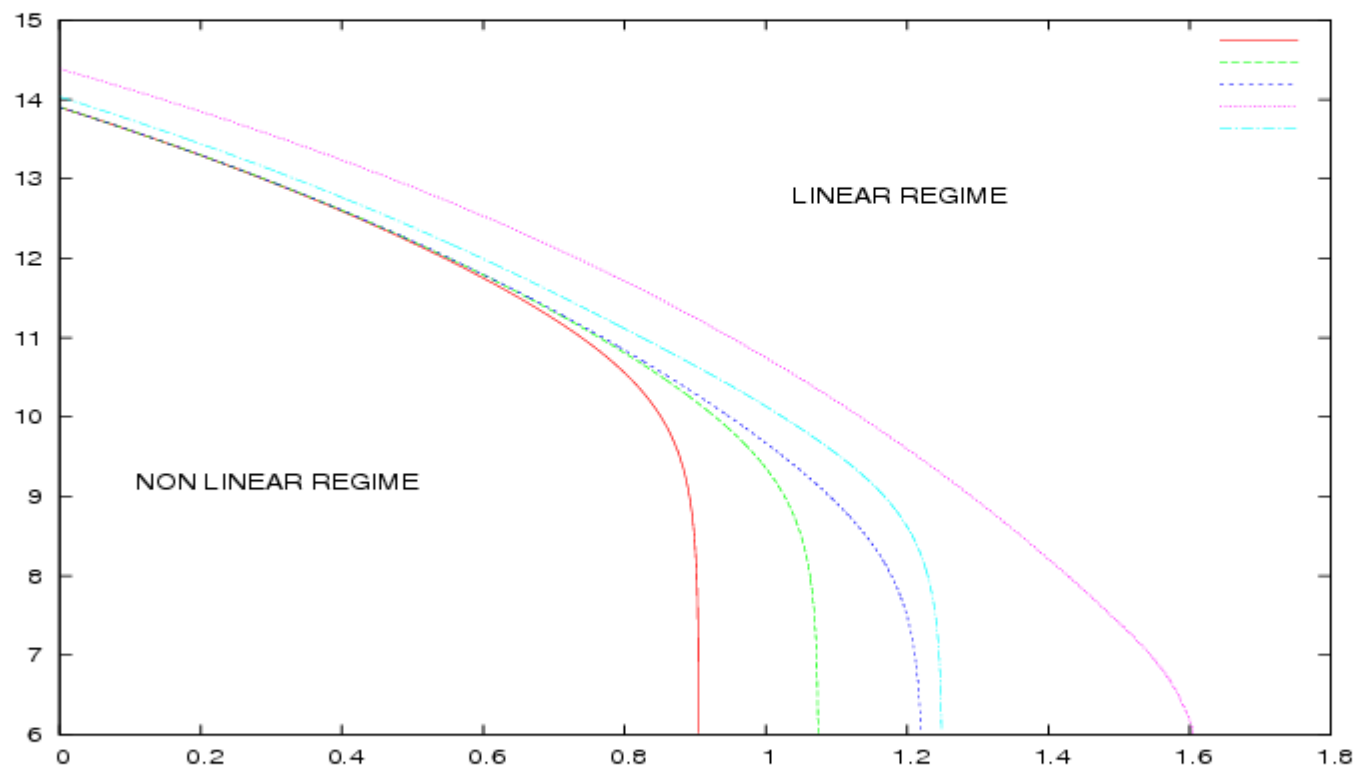


CDM, 1 keV, 2 keV, 4 keV WDM decoupling in equilibrium.

Linear and non-linear regimes in z and R

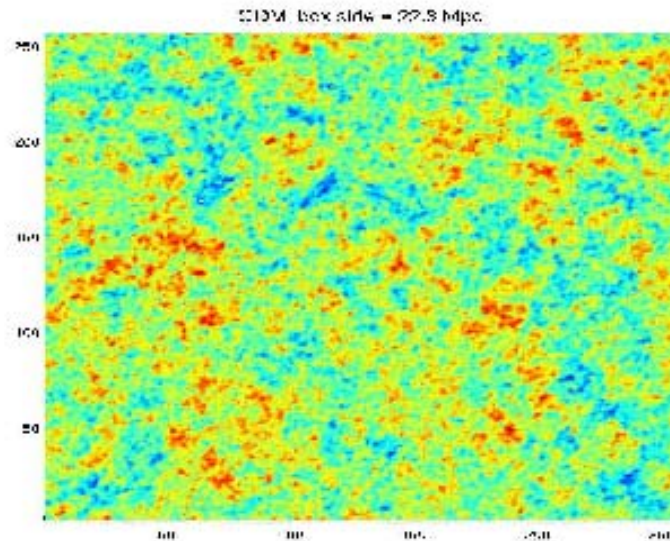
$\sigma^2(R, z) \sim 1$: borderline between linear and non-linear regimes. Objects (galaxies) of scale R and mass $\sim R^3$ start to form when this scale becomes non-linear.

Smaller objects form **earlier**.



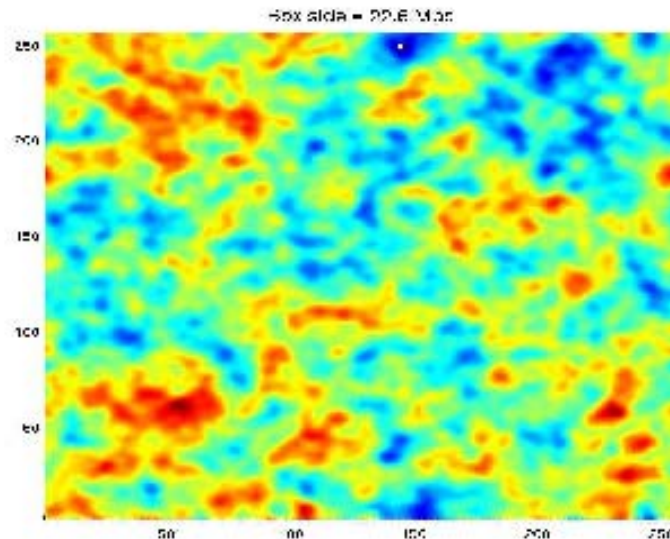
$\log M/M_{\odot}$ vs. $\log(z+1)$ for **CDM**, **1 keV**, **2 keV**, **4 keV** DM particles decoupling in equil, and 1 keV (light-blue) sterile ν .

WDM vs. CDM linear fluctuations today



Box side = 22.6 Mpc. [C. Destri, private communication].

WDM:



Λ CDM and Λ WDM simulations vs. astronomical observations



Λ CDM

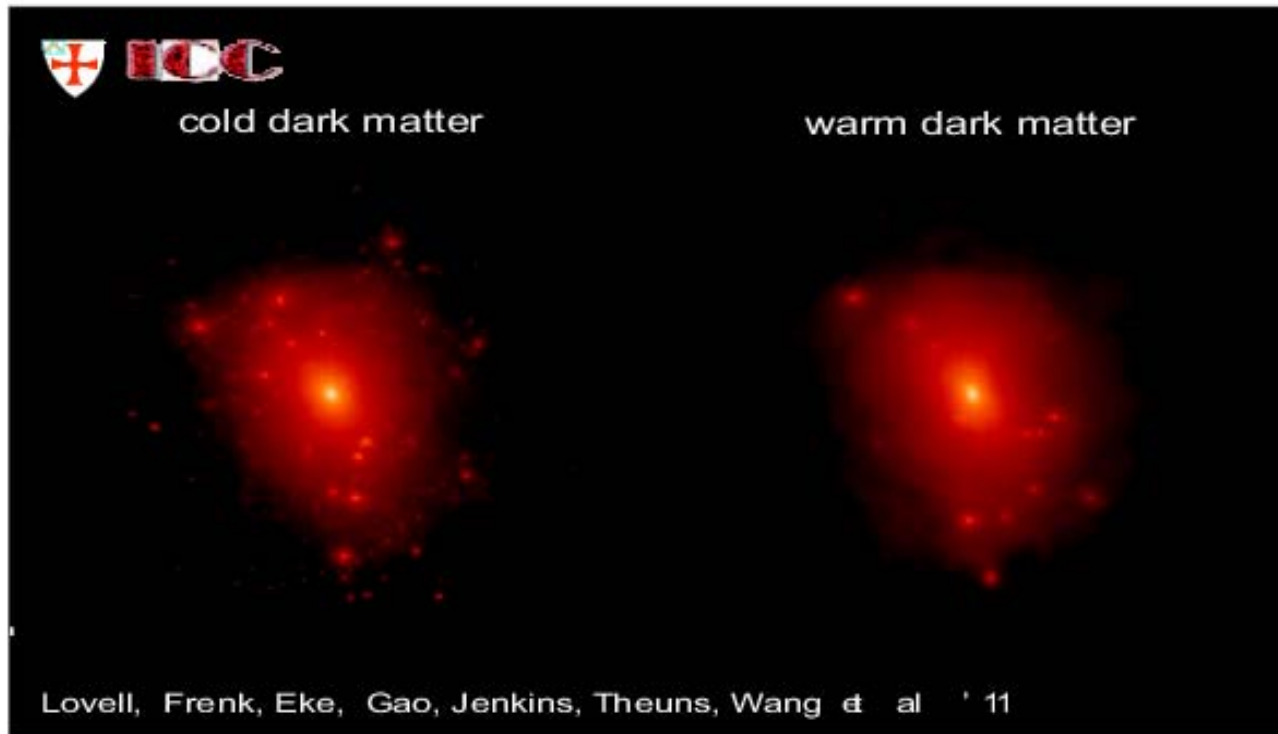


observations



1keV WDM

N-body WDM Simulations



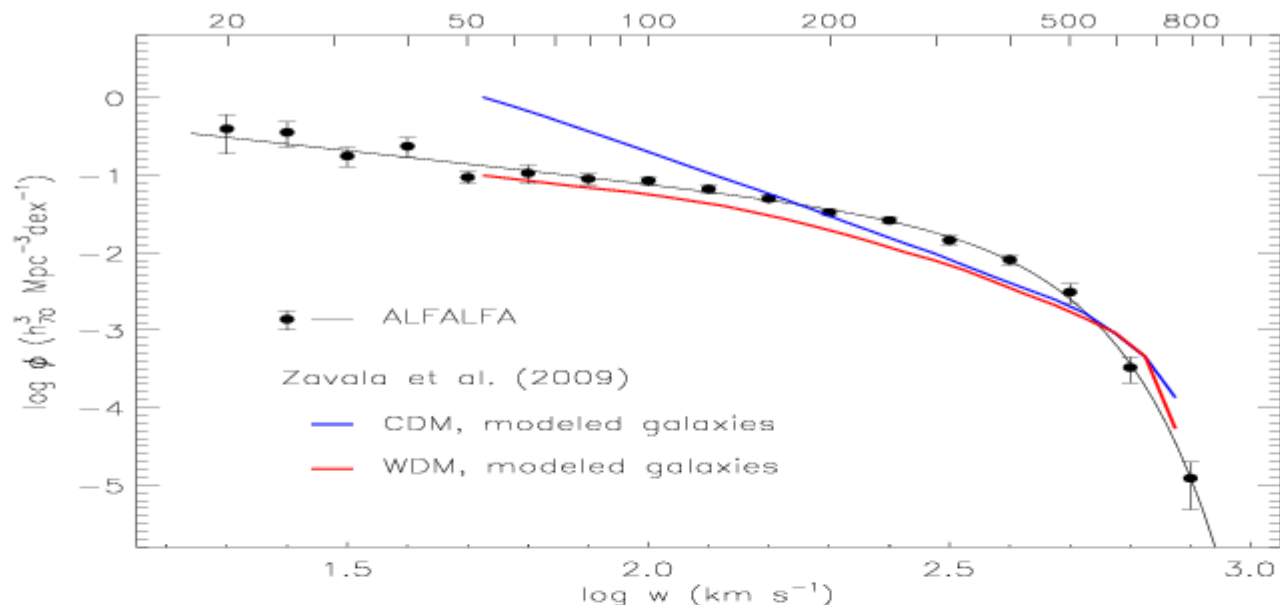
Wednesday, 15 June 2011

WDM subhalos are **less concentrated** than CDM subhalos.

WDM subhalos have the **right concentration** to host the bright Milky Way satellites.

Lovell et al. arXiv:1104.2929

Velocity widths in galaxies



Velocity widths in galaxies from 21cm HI surveys. ALFALFA survey **clearly favours WDM** over CDM. (Papastergis et al. 2011, Zavala et al. 2009).

Notice that the WDM **red** curve is for $m = 1$ keV WDM particle decoupling at thermal equilibrium.

The 1 keV WDM curve falls somehow below the data suggesting a slightly **larger** WDM particle mass.

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**.

Galaxy Formation and Evolution

Galaxies naturally grow through merging in CDM models.

Observations show that galaxy mergers are **rare** ($< 10\%$).

Galaxies often exhibit baryonic matter disks that CDM+baryon models **cannot explain** without mergers. (J. Kormendy, R. Bender et al. ApJ 2010 and many refs.).

On the other hand CDM generically produces dark disks. **No dark disk** in the Milky Way (Moni Bidin et al. ApJ 2010).

Galaxy formation within CDM models suffers of **serious discrepancies** with observations.

WDM simulations are **needed**.

WDM simulations at present:

A. Kamada et al. (IPMU, Tokyo), M. Lovell et al. (Durham), K. Markovic et al. (Munich), S. Paduroiu et al. (Zurich, Geneva), A. Schneider et al. (Zurich), CLUES collaboration (Berlin-Madrid-Jerusalem), E. Polisensky et al. (Maryland).

Galaxy Density Profiles: Cores vs. Cusps

Astronomical observations **always** find cored profiles for DM dominated galaxies. Selected references:

J. van Eymeren et al. A&A (2009), M. G. Walker, J. Peñarrubia, Ap J (2012). Reviews by de Blok (2010), Salucci & Frigerio Martins (2009).

Galaxy profiles in the **linear regime**: core size \sim free streaming length (de Vega, Salucci, Sanchez, 2010)=

$$\text{halo radius } r_0 = \begin{cases} 0.05 \text{ pc cusps for CDM (} m > \text{ GeV).} \\ 50 \text{ kpc cores for WDM (} m \sim \text{ keV).} \end{cases}$$

N-body simulations for CDM give **cusps** (NFW profile).

N-body simulations for WDM :

quantum physics needed for fermionic DM !!!

CDM simulations give a precise value for the concentration $\equiv R_{\text{virial}}/r_0$. CDM concentrations **disagree** with observed

THE MASS OF THE

DARK MATTER PARTICLE

→ **Compute** from 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 $D(z)$

→ **Confront** 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 self-gravity interactions: **the range of Z is computed.***

OBSERVATIONS

The observed dark matter energy density observed today has the value $\rho_{DM} = 0.228 (2.518 \text{ meV})^4$.

In addition, compilation of galaxy observations yield the one dimensional velocity dispersion σ and the radius L in the ranges

$$6.6 \text{ km/s} \leq \sigma \leq 11.1 \text{ km/s} , \quad 0.5 \text{ kpc} \leq L \leq 1.8 \text{ kpc}$$

And the Phase-space Density today (with a precision of a factor 10) has the value :

$$D(0) \sim 5 \times 10^3 \text{ [keV/cm}^3\text{]} (\text{km/s})^{-3} = (0.18 \text{ keV})^4 .$$

→ **Compilation of observations of galaxies candidates for DM structure, are compatible with a core of smooth central density and a low mean mass density $\sim 0.1 \text{ Msun /pc}^3$ rather than with a cusp.**

→ **Dark matter particles can decouple being ultrarelativistic or non-relativistic. Dark matter must be non-relativistic during structure formation in order to reproduce the observed small structure at $\sim 2 - 3 \text{ kpc}$.**

→ **In addition, the decoupling can occur at local thermal equilibrium or out of local thermal equilibrium. All these cases have been considered in our analysis.**

Dark Matter Particles

DM particles can decouple being **ultrarelativistic** or non-relativistic. They can decouple **at or out** of thermal equilibrium.

The DM distribution function **freezes out** at decoupling. All DM physical quantities can be obtained from it in the early universe (before structure formation) as energy density $\rho_{DM}(t)$ and velocity fluctuations $\langle \sigma_{DM}^2(t) \rangle$.

The **phase-space density** $Q \equiv \rho_{DM}/\sigma_{DM}^3$ is **invariant** under the cosmological expansion and can **only decrease** under self-gravity interactions (gravitational clustering).

Early universe value: $Q_{prim} = \rho_{prim}/\sigma_{prim}^3 = \frac{3\sqrt{3}}{2\pi^2} g \frac{I_2^{\frac{5}{2}}}{I_4^{\frac{3}{2}}} m^4$

I_2 and I_4 are momenta of the DM distribution function.

g : # of internal degrees of freedom of the DM particle,

$1 \leq g \leq 4$.

The 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**:
 $1 \text{ keV} \lesssim m \lesssim 10 \text{ keV}$.

This is true both for DM decoupling in or out of equilibrium, bosons or fermions.

It is **independent of the particle physics** model.

Out of thermal equilibrium decoupling

Results for m and g_d on the **same** scales for DM particles decoupling UR **out of thermal equilibrium**.

For the χ model of sterile neutrinos where decoupling is out of thermal equilibrium:

$$0.56 \text{ keV} \lesssim m_\nu Z^{-\frac{1}{4}} \lesssim 1.0 \text{ keV} \quad , \quad 15 \lesssim g_d Z^{-\frac{1}{4}} \lesssim 84$$

$$\text{Therefore, } 0.6 \text{ keV} \lesssim m_\nu \lesssim 10 \text{ keV} \quad , \quad 20 \lesssim g_d \lesssim 850.$$

Relics decoupling non-relativistic:

similar bounds: $\text{keV} \lesssim m \lesssim \text{MeV}$

D. Boyanovsky, H. J. de Vega, N. Sanchez,
Phys. Rev. D 77, 043518 (2008), arXiv:0710.5180.

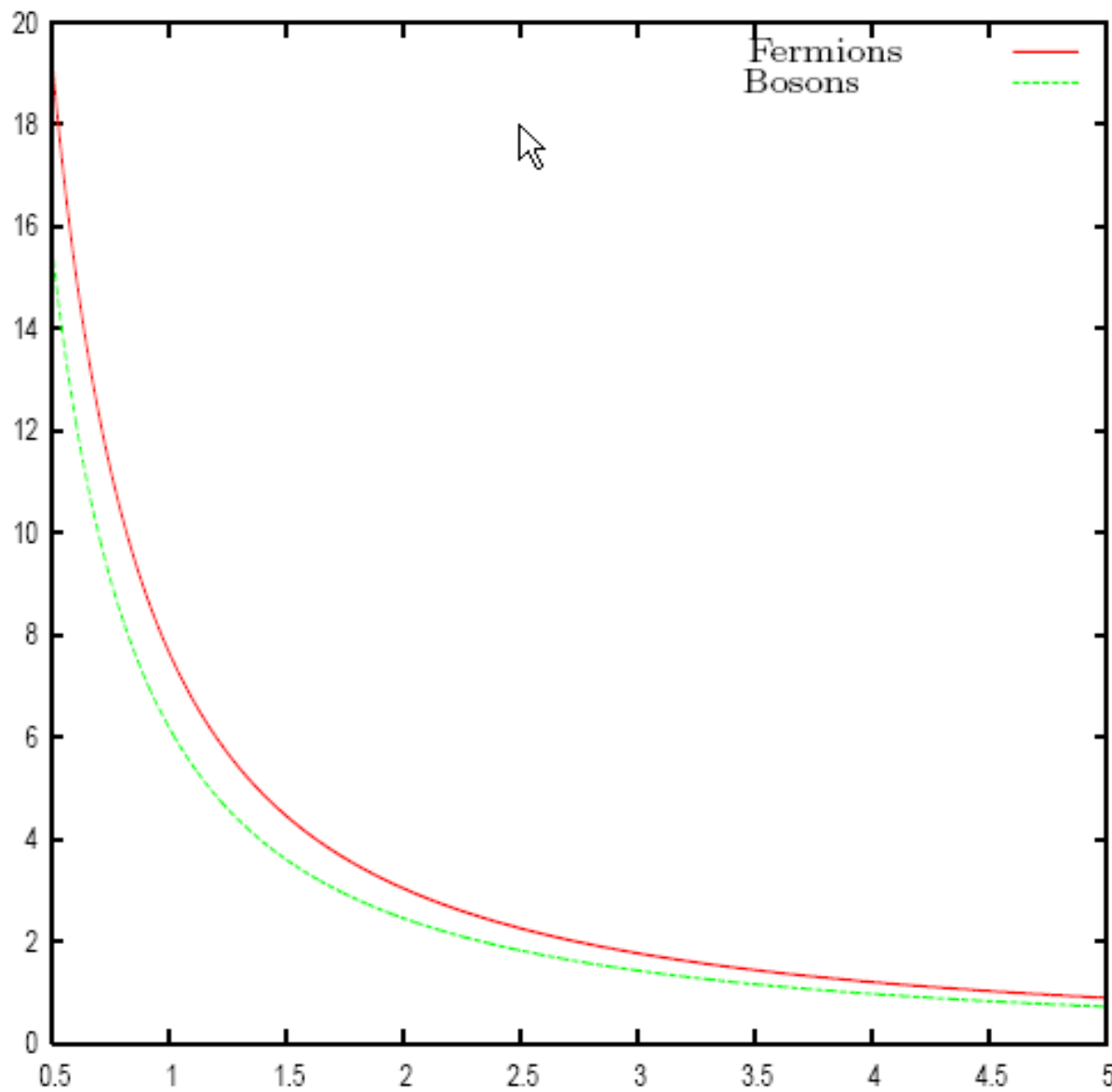
H. J. de Vega, N. G. Sanchez, MNRAS 404, 885 (2010),
arXiv:0901.0922.

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

$$0.76 \text{ kpc } (1 + z)^{-1/2} < \lambda_{\text{fs}}(z) < 16.3 \text{ kpc } (1 + z)^{-1/2}$$

$$0.45 \cdot 10^3 M_{\text{sun}} < M_{\text{J}}(z) (1 + z)^{-3/2} < 0.45 \cdot 10^7 M_{\text{sun}}$$

- These values at $z = 0$ are consistent and of order of the small dark matter structures observed today
- By the beginning of the matter era $z \sim 3200$, the masses are of the order of galactic masses $10^{12} M_{\text{sun}}$ and the comoving free-streaming length is of the order of the galaxy sizes today $\sim 100 \text{ kpc}$



The free-streaming wavelength today in kpc vs. the dark matter particle mass in keV. It decreases for increasing mass m and shows little variation with the particle statistics (fermions or bosons).

- **The mass of the dark matter particle, independent of the particle model, is in the keV scale.**

Robust result. No assumption about the particle physics model of the dark matter particle.

keV DM mass much larger than temperature in matter dominated era (which is less than 1 eV)

m and 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 $10^{1/4} \sim 1.8$.

• dark matter annihilation cross-section $\sigma_0 : \sigma_0 > (0.239 - 0.956) 10^{-9} \text{ GeV}^{-2}$ and $\sigma_0 < 3200 \text{ m GeV}^{-3}$.
the dark matter non gravitational self-interaction is negligible (consistent with structure formation and observations, X-ray, optical and lensing observations of the merging of galaxy clusters).

• **Typical "wimps"** (weakly interacting massive particles) **with mass $m = 100 \text{ GeV}$ and $T_d = 5 \text{ GeV}$** would require a huge **$Z \sim 10^{23}$** , well above the upper bounds obtained and cannot reproduce the observed galaxy properties.

Wimps produce extremely short free-streaming or Jeans length today $\lambda_{fs}(0) = 3.51 10^{-4} \text{ pc} = 72.4 \text{ AU}$ that would correspond to unobserved structures much smaller than the galaxy structure. **[TOO cold]**

RESULTS on DARK MATTER :

- (i) the mass of the **dark matter particle is in the keV scale**, T_d can be around **100 GeV**.
- (ii) The **free-streaming length** 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, $10^{12} M_{\text{sun}}$** .
- (iii) Dark matter **self-interactions** (other than grav.) **are negligible**.
- (iv) The **keV scale mass** dark matter determines **cored** (non cusped) dark matter halos.
- (v) DM candidates with **typical high masses 100 GeV (wimps) cusped profiles, result strongly disfavored**.

keV SCALE DARK MATTER PARTICLES REPRODUCE:

**→ OBSERVED GALAXY DENSITIES
AND VELOCITY DISPERSIONS**

→ OBSERVED GALAXY DENSITY PROFILES

**-> OBSERVED SURFACE DENSITY VALUES OF
DARK MATTER DOMINATED GALAXIES**

Galaxies

Physical variables in galaxies:

a) **Nonuniversal** quantities: mass, size, luminosity, fraction of DM, DM core radius r_0 , central DM density ρ_0 , ...

b) **Universal** quantities: surface density $\mu_0 \equiv r_0 \rho_0$ and DM density profiles. M_{BH}/M_{halo} (or the halo binding energy).

The galaxy variables are related by **universal** empirical relations. Only **one variable** remains free.

Universal quantities may be **attractors** in the dynamical evolution.

Universal DM density profile in Galaxies:

$$\rho(r) = \rho_0 F\left(\frac{r}{r_0}\right), \quad F(0) = 1, \quad x \equiv \frac{r}{r_0}, \quad r_0 = \text{DM core radius.}$$

Empirical cored profiles: $F_{Burkert}(x) = \frac{1}{(1+x)(1+x^2)}$.

Cored profiles **do reproduce** the astronomical observations.

The constant surface density in DM and luminous galaxies

The Surface density for dark matter (DM) halos and for luminous matter galaxies defined as: $\mu_{0D} \equiv r_0 \rho_0$,

r_0 = halo core radius, ρ_0 = central density for DM galaxies

$$\mu_{0D} \simeq 120 \frac{M_{\odot}}{\text{pc}^2} = 5500 (\text{MeV})^3 = (17.6 \text{ MeV})^3$$

5 kpc $< r_0 < 100$ kpc. For luminous galaxies $\rho_0 = \rho(r_0)$.
Donato et al. 09, Gentile et al. 09. [$\mu_{0D} = g$ in the surface].

Universal value for μ_{0D} : **independent** of galaxy luminosity for a large number of galactic systems (spirals, dwarf irregular and spheroidals, elliptics) spanning over 14 magnitudes in luminosity and of different Hubble types.

Similar values $\mu_{0D} \simeq 80 \frac{M_{\odot}}{\text{pc}^2}$ in interstellar molecular clouds of size r_0 of different type and composition over scales $0.001 \text{ pc} < r_0 < 100 \text{ pc}$ (Larson laws, 1981).

DM surface density from linear Boltzmann-Vlasov eq

The distribution function of the decoupled DM particles:

$f(\vec{x}, \vec{p}; t) = g f_0^{DM}(p) + F_1(\vec{x}, \vec{p}; t)$, $f_0^{DM}(p) =$ zeroth order DM distribution function in or out of thermal equilibrium.

We evolve the distribution function $F_1(\vec{x}, \vec{p}; t)$ according to the **linearized Boltzmann-Vlasov** equation since the end of inflation. The DM density fluctuations are given by

$$\Delta(t, \vec{k}) \equiv m \int \frac{d^3 p}{(2\pi)^3} \int d^3 x e^{-i \vec{x} \cdot \vec{k}} F_1(\vec{x}, \vec{p}; t)$$

Today: $\Delta(\text{today}, \vec{k}) = \rho_{DM} \bar{\Delta}(z=0, k) \sqrt{V} |\phi_k| g(\vec{k})$,

where $\bar{\Delta}(z, k)$ obeys a Volterra integral equation, the **primordial inflationary** fluctuations are:

$$|\phi_k| = \sqrt{2} \pi \frac{|\Delta_0|}{k^{\frac{3}{2}}} \left(\frac{k}{k_0} \right)^{\frac{n_s - 1}{2}} , \quad g(\vec{k}) \text{ is a random gaussian field,}$$

$V =$ phase-space volume at horizon re-entering

$$|\Delta_0| \simeq 4.94 \cdot 10^{-5}, \quad n_s \simeq 0.964, \quad k_0 = 2 \text{ Gpc}^{-1}, \quad \text{WMAP7} .$$

Linear density profile

The matter density fluctuations $\rho_{lin}(r, z)$ are given at redshift z by

$$\rho_{lin}(r, z) = \frac{1}{2\pi^2 r} \int_0^\infty k dk \sin(k r) \Delta(k, z) \quad \text{for } g(\vec{k}) = 1$$

The **linear profile today** results:

$$\rho_{lin}(x) = 0.034 \rho_{DM} \frac{q_p^{\frac{n_s+2}{3}}}{x} I_3 \int_0^\infty \gamma^{n_s/2-1} d\gamma \sin(\gamma x) \bar{\Delta}(z, \gamma)$$

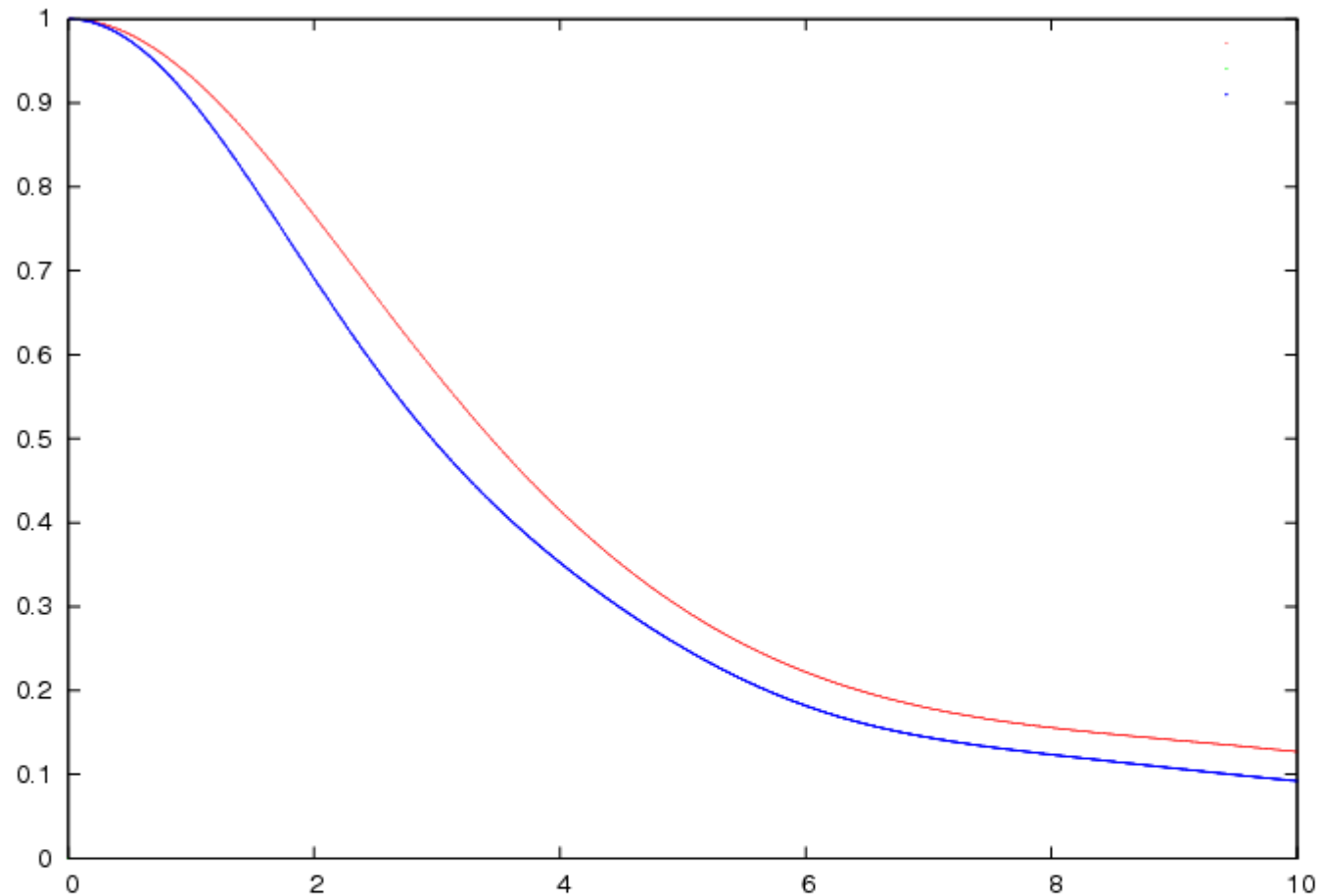
where $\gamma \equiv k r_{lin}$ and $x \equiv r/r_{lin}$.

I_n and $\bar{\Delta}(z, \gamma)$ depend on the frozen-out DM distribution $f_0^{DM}(Q)$.

Notice that $\bar{\Delta}(z, \gamma) \simeq \frac{1}{z+1} \bar{\Delta}(0, \gamma)$

Therefore, the profile shape turns to be redshift independent in the MD/ Λ era.

Density profiles in the linear approximation



Profiles $\rho_{lin}(r)/\rho_{lin}(0)$ vs. $x \equiv r/r_{lin}$.

Fermions decoupling ultrarelativistically **in** and **out** of thermal equilibrium. The halo radius r_0 is proportional to r_{lin} : $r_0 = \beta r_{lin}$. $\beta_{in\,equil} = 5.565$, $\beta_{out\,equil} = 5.013$.

Density profiles in the linear approximation

Density profiles turn to be **cored** at scales $r \ll r_{lin}$.

Intermediate regime $r \gtrsim r_{lin}$:

$$\rho_{lin}(r) \stackrel{r \gtrsim r_{lin}}{=} c_0 \left(\frac{r_{lin}}{r}\right)^{1+n_s/2} \rho_{lin}(0) \quad , \quad 1 + n_s/2 = 1.482.$$

$\rho_{lin}(r)$ **scales** with the **primordial spectral index** n_s .

The theoretical linear results **agree** with the universal empirical behaviour $r^{-1.6 \pm 0.4}$: M. G. Walker et al. (2009) (observations), I. M. Vass et al. (2009) (simulations).

The agreement between the linear theory and the observations is **remarkable**.

In the asymptotic regime $r \gg r_{lin}$ the small k behaviour of

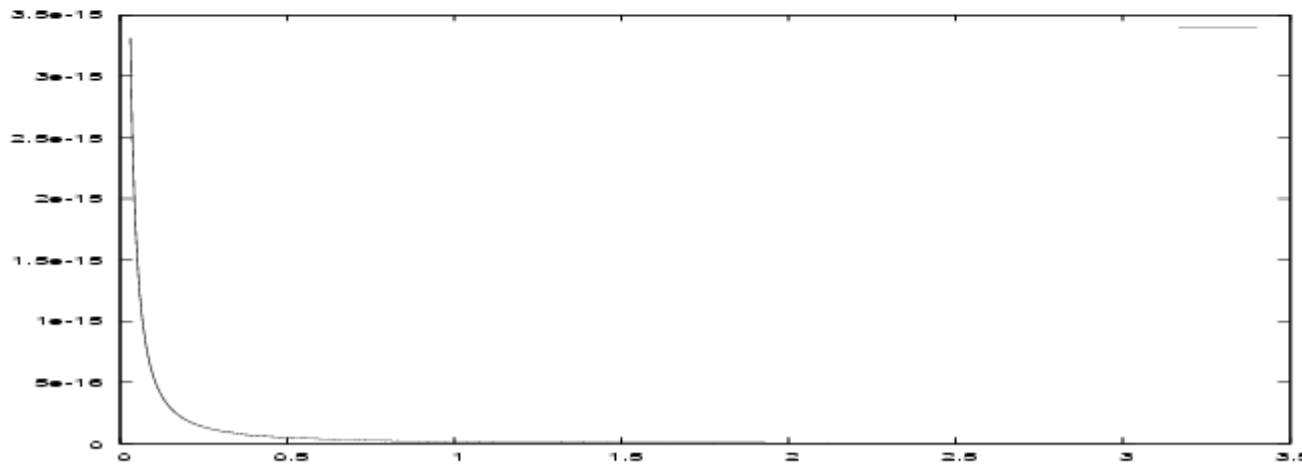
$\Delta(k, t_{today}) \stackrel{k \rightarrow 0}{=} c_1 (k r_{lin})^s$ with $s \simeq 0.5$ implies the presence

of a tail: $\rho_{lin}(r) \stackrel{r \gg r_{lin}}{\simeq} c \left(\frac{r_{lin}}{r}\right)^2$.

Wimps vs. galaxy observations

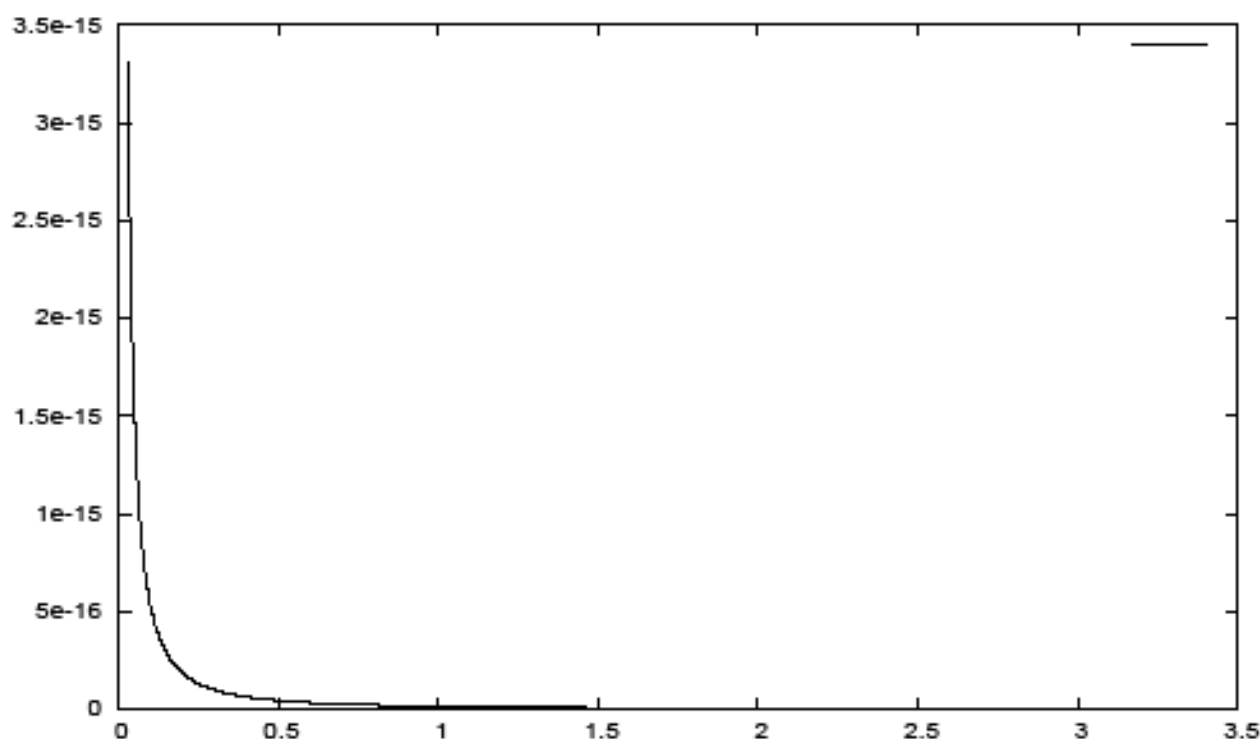
	Observed Values	Wimps in linear theory
r_0	5 to 52 kpc	0.045 pc
ρ_0	1.57 to $19.3 \times 10^{-25} \frac{\text{g}}{\text{cm}^3}$	$0.73 \times 10^{-14} \frac{\text{g}}{\text{cm}^3}$
$\sqrt{v^2_{halo}}$	79.3 to 261 km/sec	0.243 km/sec

The wimps values strongly disagree by **several order of magnitude** with the observations.



$\rho_{lin}(r)_{wimp}$ in g/cm^3 vs. r in pc. Exhibits a cusp behaviour for $r \geq 0.03$ pc.

Linear CDM profiles are cusped



$\rho_{lin}(r)_{CDM}$ in g/cm^3 vs. r in pc.

Exhibits a cusp behaviour for $r \gtrsim 0.03$ pc. (Here $m_{CDM} = 100$ GeV).

Observations in DM dominated galaxies always exhibit **cores**.

Galaxy Density Profiles: Cores vs. Cusps

Astronomical observations **always** find cored profiles for DM dominated galaxies. Selected references:

J. van Eymeren et al. A&A (2009), M. G. Walker, J. Peñarrubia, Ap J (2012). Reviews by de Blok (2010), Salucci & Frigerio Martins (2009).

Galaxy profiles in the **linear regime**: core size \sim free streaming length (de Vega, Salucci, Sanchez, 2010)=

$$\text{halo radius } r_0 = \begin{cases} 0.05 \text{ pc cusps for CDM (} m > \text{ GeV).} \\ 50 \text{ kpc cores for WDM (} m \sim \text{ keV).} \end{cases}$$

N-body simulations for CDM give **cusps** (NFW profile).

N-body simulations for WDM : complex issue.

CDM simulations give a precise value for the concentration $\equiv R_{\text{virial}}/r_0$. CDM concentrations **disagree** with the values needed to fit observed profiles.

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:

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

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, $\sigma^2(\vec{r}) \equiv \langle v^2(\vec{r}) \rangle / 3$

$K \sim 1$ 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 $\hbar \rightarrow 0$ and the bound disappears.

Classical physics breaks down near the galaxy center

N -body simulations point to cuspy phase-space densities

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

Q_s = mean phase space density in the halo.

$Q(r)$ derived within classical physics tends to infinity for $r \rightarrow 0$ **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: $30 < \frac{r_s}{\text{pc}} < 5 \cdot 10^4$, $2 \cdot 10^{-5} < \frac{\hbar^{\frac{3}{2}} \sqrt{Q_s}}{(\text{keV})^2} < 0.6$

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.

Quantum bounds on the galaxy core size

Combining the virial theorem

$$\sigma_s^2 = \frac{G M_s}{3 r_s} \quad \text{and} \quad M_s = \frac{4}{3} \pi r_s^3 \rho_s$$

with the quantum bound on $Q(r)$ yields that classical physics breaks down for $r < r_q$ where

$$r_q = \frac{1.5 \times 3^{\frac{1}{4}}}{\sqrt{\pi K m^2}} \left(\frac{\hbar}{\sqrt{G}} \right)^{\frac{3}{2}} \left(\frac{r_s}{M_s} \right)^{\frac{1}{4}} = \frac{0.5879}{\sqrt{K}} \left(\frac{r_s}{\text{pc}} \frac{10^6 M_\odot}{M_s} \right)^{\frac{1}{4}} \left(\frac{\text{keV}}{m} \right)^2 \text{ pc}$$

Conclusion: r_q is in the parsec range for WDM $m \sim \text{keV}$.

r_q is the **minimal** possible value for the core radius.

The core radius can be **well above** r_q which corresponds to **maximally packed fermions** around the center of the galaxy.

For diluted objects as galaxies core radii much larger than r_q are expected.

In atoms the electrons phase-space density turns to be **significantly** below the Pauli quantum bound.

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 !

Dwarf galaxies as quantum objects

de Broglie wavelength of DM particles $\lambda_{dB} = \frac{1}{m \sigma}$

$d =$ Average distance between particles

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

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

Observed values: $0.74 \times 10^{-3} < R \left(\frac{m}{\text{keV}}\right)^{\frac{1}{3}} < 0.70$

The **larger** R is for ultracompact dwarfs.

The **smaller** R is for big spirals.

The ratio R near unity (or above) means a
QUANTUM OBJECT.

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

Summary on quantum bounds on cores

If DM were formed by bosons the quantum bound on Q does not apply and the formation of cusps would be allowed.

Astronomical observations show that DM galaxy density profiles are **cored**.

Thus, bosonic DM turns to be **strongly** disfavoured.

In all cases, cusps of fermionic DM in the galaxy density profile are **artifacts** produced by **classical** physics computations irrespective of the nature of dark matter (HDM, WDM, CDM).

Quantum physics, namely the Pauli principle, **rule out** galaxy cusps for fermionic dark matter.

C. Destri, H. J. de Vega, N. G. Sanchez, 'Fermionic warm dark matter produces galaxy cores in the observed scales', arXiv:1204.3090.

Quantum pressure vs. gravitational pressure

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

$v = \text{mean velocity}$, 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: $P_q = P_G \implies M_q = \frac{9}{2 \sqrt{\pi} m^2} \left(\frac{\hbar v}{G} \right)^{\frac{3}{2}} =$

$$= 0.797 \dots 10^6 M_{\odot} \left(\frac{\text{keV}}{m} \right)^2 \left(\frac{v}{10 \frac{\text{km}}{\text{s}}} \right)^{\frac{3}{2}}$$

for WDM $M_q \sim$ **mass of dwarf galaxies !!**

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

Self-gravitating Fermions in the Thomas-Fermi approach

WDM is non-relativistic in the MD era.

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

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 $\implies \frac{d\mu}{dr}(0) = 0$.

Density $\rho(r)$ in terms of the distribution function $f(E)$:

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

Thomas-Fermi approximation: system of ordinary nonlinear differential equations. Determine the chemical potential $\mu(r)$

Boundary condition: $r = R = R_{200} \sim R_{vir}$.

At $r = R_{200}$ the DM density $\simeq 200 \bar{\rho}_{DM}$.

Self-gravitating Fermions 2

In **dimensionless variables** the Thomas-Fermi equations for self-gravitating fermions:

$$\frac{d^2 \nu}{d\xi^2} + \frac{2}{\xi} \frac{d\nu}{d\xi} + 3 \beta(\nu(\xi)) = 0 \quad , \quad \beta(\nu) \equiv \int_0^\infty y^2 dy \Psi(y^2 - \nu)$$

Here: $\mu(r) = E_0 \nu(\xi) \quad , \quad r = L_0 \xi \quad , \quad f(E) = \Psi \left[\frac{E}{E_0} \right]$

E_0 = characteristic energy of DM particles at decoupling.

L_0 = characteristic length.

L_0 emerges from the dynamical Thomas-Fermi equations

$$L_0 \equiv \frac{\sqrt{3} \pi \hbar^3}{\sqrt{G} (2m)^2} \left(\frac{2m}{E_0} \right)^{\frac{1}{4}} \quad , \quad \rho(r) = \frac{m^4}{\pi^2 \hbar^3} \left(\frac{2E_0}{m} \right)^{\frac{3}{2}} \beta(\nu(\xi))$$

Thermal equilibrium: $\Psi_{FD}(x) = \frac{1}{e^x + 1} \quad ,$

Dodelson-Widrow model: $\Psi(x) = \frac{f_0}{m} \frac{1}{e^x + 1} \quad , \quad f_0 \simeq 0.043 \text{ keV}$

ν -MSM model: $\Psi(x) = 2 \tau \sqrt{\frac{\pi}{x}} \sum_{n=1}^{\infty} \frac{e^{-n x}}{n^{\frac{5}{2}}} \quad , \quad \tau \simeq 0.03$

Thomas-Fermi approximation: solutions

$$M(R) = \frac{(3\pi)^2 \hbar^6}{256 G^3 m^8 R^3} \xi_0^5 |\nu'(\xi_0)|$$

$$P(r) = \frac{\pi^{4/3}}{3} \hbar^2 \left[\frac{\rho(0)}{\beta(\xi_0) m^4} \right]^{5/3} \int_0^\infty y^4 dy \Psi(y^2 - \nu(\xi))$$

L_0 and $M(R)$ turn to be of the order of the Jeans' length and the Jeans' mass, respectively.

The chemical potential at $r = 0$ fixed by the value of $Q(0)$.

Using observed values of $Q(0)$, we obtain halo radius $r_s \sim 0.1 - 10$ kpc, galaxy masses $10^5 - 10^7 M_\odot$ and velocity dispersions, **all consistent** with the observations of dwarf galaxies.

The Thomas-Fermi approach gives **realistic halo radii**, larger than the quantum lower bound r_q , as expected.

Fermionic WDM **treated quantum mechanically is able to reproduce** the observed DM cores of galaxies.

Particle physics candidates for DM

No particle in the Standard Model of particle physics (SM) can play the role of DM.

Many extensions of the SM can be envisaged to include a DM particle with mass in the **keV scale** and weakly enough coupled to the Standard Model particles to fulfill **all** particle physics experimental constraints.

Main candidates in the **keV mass scale**: **sterile neutrinos**, gravitinos, light neutralino, majoron ...

Particle physics **motivations** for sterile neutrinos:

There are both **left** and **right** handed quarks (with respect to the chirality).

It is natural to have right handed neutrinos ν_R besides the known left-handed neutrino. **Quark-lepton similarity**.

keV Sterile Neutrino Warm Dark Matter

Sterile neutrinos can decay into an active-like neutrino and a monochromatic X-ray photon with an energy half the mass of the sterile neutrino. **Observing the X-ray photon provides a way to observe sterile neutrinos in DM halos.**

WDM keV sterile neutrinos can be copiously produced in the supernovae cores. SN stringently constrain the neutrino mixing angle squared to be 10^{-9} for $m > 100$ keV (in order to avoid excessive energy lost) but for smaller masses the SN bound is not so direct. **Within the models worked out till now, mixing angles are essentially unconstrained by SN in the keV mass range.**

Sterile neutrinos are produced **out of thermal equilibrium** and their production can be non-resonant (in the absence of lepton asymmetries) **or resonantly enhanced** (if lepton asymmetries are present).

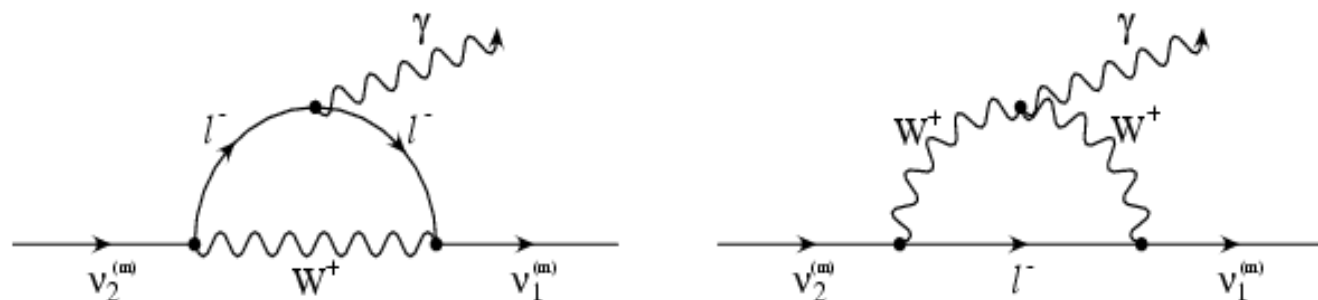
X-ray detection of DM sterile neutrinos

Sterile neutrinos ν_s decay into active neutrinos ν_a plus **photons** (γ) with a width:

$$\Gamma_{\nu_s \rightarrow \nu_a} = \frac{9}{256 \pi^4} \alpha G_F^2 \sin^2 \theta m_{\nu_s}^5 = \frac{\sin^2 \theta}{1.8 \cdot 10^{21} \text{ sec}} \left(\frac{m_{\nu_s}}{\text{keV}} \right)^5$$

Pal & Wolfenstein (1982). $E_\gamma = m_{\nu_s}/2 \Rightarrow$ X-rays.

$$\Gamma_{\nu_s \rightarrow \nu_a} \ll \frac{1}{\text{Age of the universe} = 4.32 \cdot 10^{17} \text{ sec}}$$



These X-rays **may be seen** in the sky looking to galaxies !

P L Biermann and A. Kusenko, PRL (2006)

A. Kusenko and M. Loewenstein, ApJ (2010), 1σ detection of a 5 keV sterile neutrino.

C. R. Watson et al. arXiv:1111.4217. More papers ...

Further Experiments to detect Sterile Neutrinos

Ly α forest observations give limits on the sterile ν mass. However, it is the most sensitive method to the difficult-to-characterize non-linear growth of baryonic and DM structures. As a result, there are **significant** discrepancies between the reported mass lower limits.

Supernovae: θ unconstrained, $1 < m < 10$ keV
(G. Raffelt & S. Zhou, PRD 2011).

CMB: WDM decay distorts the blackbody CMB spectrum. The projected PIXIE satellite mission (A. Kogut et al.) can measure WDM sterile neutrino mass.

Rhenium and Tritium **beta decay** (MARE, KATRIN).
Theoretical analysis: H J de V, O. Moreno, E. Moya de Guerra, M. Ramón Medrano, N. Sánchez, arXiv:1109.3452.

Sterile Neutrinos may be observed in **electron capture** (EC) as in $^{163}\text{Ho} \rightarrow ^{163}\text{Dy}$, MARE experiment (Nucciotti et al.)

Summary: keV scale DM particles

- **Reproduce** the phase-space density observed in dwarf spheroidal and spiral galaxies (dV S, MNRAS 2010).
- Fermionic WDM provide **cored** galaxy profiles through **quantum effects** in agreement with observations (Destri, de Vega, Sanchez, 2012).
- The galaxy surface density $\mu_0 \equiv \rho_0 r_0$ is **universal** up to $\pm 10\%$ according to the observations. Its value $\mu_0 \simeq (18 \text{ MeV})^3$ is reproduced by WDM (dV S S, New Astronomy, 2012). CDM simulations give 1000 times the observed value of μ_0 (Hoffman et al. ApJ 2007).
- **Alleviate** the satellite problem which appears when wimps are used (Avila-Reese et al. 2000, Götz & Sommer-Larsen 2002, Markovic et al. JCAP 2011)
- **Alleviate** the voids problem which appears when wimps are used (Tikhonov et al. MNRAS 2009).

Summary and Conclusions

- Combining **theoretical** evolution of fluctuations through the Boltzmann-Vlasov equation with **galaxy data** points to a DM particle mass 3 - 10 keV. T_d turns to be model dependent. The keV mass scale holds **independently** of the DM particle physics model.
- Universal Surface density in DM galaxies [$\mu_{0D} \simeq (18 \text{ MeV})^3$] explained by keV mass scale DM. Density profile scales and decreases for intermediate scales with the **spectral index** n_s : $\rho(r) \sim r^{-1-n_s/2}$ and $\rho(r) \sim r^{-2}$ for $r \gg r_0$.

H. J. de Vega, P. Salucci, N. G. Sanchez, 'The mass of the dark matter particle from theory and observations', *New Astronomy*, 17, 653 (2012).

H. J. de Vega, N. Sanchez, 'Model independent analysis of dark matter points to a particle mass at the keV scale', *MNRAS* 404, 885 (2010).

Summary: keV scale DM particles

- All direct searches of DM particles look for $m \gtrsim 1$ GeV. DM mass in the keV scale explains why nothing has been found ... e^+ and \bar{p} excess in cosmic rays may be explained by astrophysics: P. L. Biermann et al. (2009), P. Blasi, P. D. Serpico (2009).
- Galaxies from Wimps simulations are too small (Ryan Joung et al. 2009, Holz & Perlmutter 2010). keV scale DM may alleviate this problem.
- Velocity widths in galaxies from 21cm HI surveys. ALFALFA survey clearly favours WDM over CDM. Papastergis et al. 2011, Zavala et al. 2009

Reliable simulations with keV mass DM are needed to clarify all these issues.

Future Perspectives

DM properties from **galaxy observations**.

Chandra, Suzaku X-ray data: keV mass DM decay?

Sun models well reproduce the sun's chemical composition but not the **heliosismology** (Asplund et al. 2009).

Can DM inside the Sun help to explain the discrepancy?

Nature of **Dark** Matter? 83% of the matter in the universe.

Light DM particles are **strongly** favoured $m_{DM} \sim \text{keV}$.

Sterile neutrinos ? Other particle in the keV mass scale?

Precision determination of DM properties (mass, T_d , nature) from **better** galaxy data combined with **theory** (Boltzmann-Vlasov and simulations).

Extensive WDM N-body simulations showing substructures, galaxy formation and evolution.

Quantum dynamical evolution to compute WDM **cores**.

Bounds from MARE on sterile neutrino mass and θ .

Could KATRIN **join** the search of sterile neutrinos?

DM Dark Matter research

Present CDM status: Always increasing amount of confusion in the CDM research in the last 20 years, namely the increasing number and cyclic changing of arguments and counter-arguments and ad-hoc mechanisms introduced in CDM simulations over most of twenty years, in trying to deal with the CDM small scale problems, without really having a physical first principle derivation or control of such invoked mechanisms for the purpose (non circular motions, triaxiality, “core hidden in cusps”, mergers, baryon feedbacks, strippings,,...”, ...)



(C)DM research: present status

- **On the CDM particle side**, the problems are no less critical: So far, all the dedicated experimental searches after most of twenty years to find the theoretically proposed CDM particle candidates (Wimps) have failed.
- Its **indirect search** (invoking “**CDM annihilation**”) to explain cosmic rays positron excess, is in crisis as well, as wimps annihilation models are plagued with increasing tailoring or fine tuning, and such cosmic rays excesses are well explained and reproduced naturally by natural astrophysical process.
- The so-called and repeatedly invoked “**wimp miracle**” is nothing but one equation with three constraints, theoretically motivated by SUSY model building.

Summary (3) (Pasquale BLASI, 2011 Paris Highlights)

THIS IS ESPECIALLY TO BE KEPT IN MIND WHEN INVOKING UNCONVENTIONAL EXPLANATIONS, SUCH AS THOSE BASED ON COLD DARK MATTER ANNIHILATION

THE CDM HYPOTHESIS FOR THE POSITRON EXCESS WAS NOT THE MOST NATURAL - THE SIGNAL FROM WIMPS IS NATURALLY TOO SMALL

BUT THE THEORY WAS CONTRIVE (LEPTOPHILIC DM, BOOST FACTORS, SOMMERFIELD ENHANCEMENT) FOR THE SOLE PURPOSE OF FITTING ONE SET OF DATA (THE POSITRON FRACTION AND THE ABSENCE OF ANTIPROTON ANOMALIES).

(C)DM research: present status

- **The community engaged in CDM simulations and the super-computers is large, as well as the experimental particle physics wimp community, involving long anticipated planning in big budgets, (and large number of people), one should not be surprised if a rapid turning point would not yet operate in the CDM research community.....**
- **Still, the situation is changing rapidly in the scientific WDM research, (simply because the subject is new and WDM (essentially) works....**
- **Wimp experiments will not find the DM particle**
- **LHC will not find the DM particle**
- **Simply because they are searching at the wrong DM mass scale**
- **The DM particle is at the keV scale**

END

THANK YOU FOR YOUR ATTENTION

[DARK MATTER : FACTS AND STATUS

→ DARK MATTER DOES EXIST

→ ASTROPHYSICAL OBSERVATIONS POINTS TO THE EXISTENCE OF DARK MATTER

→ AFTER MORE THAN TWENTY YEARS OF DEDICATED DARK MATTER PARTICLE EXPERIMENTS, THE DIRECT SEARCH OF DARK MATTER PARTICLES FULLY CONCENTRATED IN “GeV WIMPS” REVEALED SO FAR, UNSUCCESSFUL. BUT DARK MATTER DOES EXIST

IN DESPITE OF THAT: PROPOSALS TO REPLACE DARK MATTER DID APPEARED:

PROPOSING TO CHANGE THE LAWS OF PHYSICS (!!!), ADDING OVER CONFUSION, MIXING , POLLUTION...

TODAY, THE DARK MATTER RESEARCH AND DIRECT SEARCH SEEMS TO SPLIT IN THREE SETS:

(1). PARTICLE PHYSICS DARK MATTER: PARTICLE BUILDING MODELS, DEDICATED LAB EXPERIMENTS, ANNIHILATING DARK MATTER, (FULLY CONCENTRATED ON “GeV WIMPS”)

(2). ASTROPHYSICAL DARK MATTER: (ASTROPHYSICAL MODELS, ASTROPHYSICAL OBSERVATIONS)

(3). NUMERICAL SIMULATIONS

*(1) and (2) DO NOT AGREE IN THE RESULTS
and (2) and (3) DO NOT FULLY AGREE NEITHER*

SOMETHING IS GOING WRONG IN THE RESEARCH ON THE DARK MATTER

WHAT IS GOING WRONG ?, [AND WHY IS GOING WRONG]

“FUT EN AVANT” (“ESCAPE TO THE FUTURE”) IS NOT THE ISSUE

CHALONGE PROGRAMME OF THE YEAR 201

* * * * * Support to the James Webb Space Telescope * * *

Chalonge Meudon Workshop 2012:

"WARM DARK MATTER GALAXY FORMATION IN AGREEMENT WITH OBSERVATIONS"

Meudon historic Castle-CIAS building, Observatoire de Paris at Meudon. Dates: 6, 7 and 8 JUNE 2012.

http://www.chalonge.obspm.fr/Cias_Meudon2012.html

16th Paris Cosmology Colloquium 2012

"THE NEW STANDARD MODEL OF THE UNIVERSE: LAMBDA WARM DARK MATTER. THEORY AND OBSERVATIONS"

Paris, Observatoire de Paris, in the Historic Perrault building
Dates: 25, 26, 27 JULY 2012

URL: <http://www.chalonge.obspm.fr/colloque2012.html>

THE SUBJECT IS MATURE

- THERE EXIST ASTRONOMICAL OBSERVATIONS AND FACILITIES
- THERE EXIST MODEL /THEORETICAL ASTROPHYSICAL RESULTS WHICH FIT, AGREE WITH THE ASTRONOMICAL OBSERVATIONS
 - THERE EXISTED, THERE EXIST MANY DARK MATTER DEDICATED PARTICLE EXPERIMENTS (ALTHOUGH FULLY CONCENTRATED IN “GeV WIMPS”)
- THERE EXIST COMPUTER AND SUPER COMPUTERS AND DIFFERENT RESEARCHER GROUPS PERFORMING WORK WITH THEM
 - THERE EXIST A CONSIDERABLE AMOUNT OF RESEARCHERS WORKING IN DARK MATTER DURING MORE THAN TWENTY YEARS

**“ FUI TE EN AVANT ” (“ESCAPE TO THE FUTURE”) IS NOT THE ISSUE
WHAT IS WRONG in the present day subject of Dark Matter?
(The Answer is Trivial and can be found in these 3 slides)**

Sterile neutrino models

Sterile neutrinos: named by Bruno Pontecorvo (1968).

- 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.
- ν -MSM model (1981)-(2006) sterile neutrinos produced by a Yukawa coupling from a real scalar χ .
- DM models must reproduce $\bar{\rho}_{DM}$, galaxy and structure formation and be consistent with particle experiments.

WDM particles in different models behave just as if their masses were different:

$$\frac{m_{DW}}{\text{keV}} \simeq 4.4 \left(\frac{m_{Thermal}}{\text{keV}} \right)^{4/3}, \quad m_{DW} \simeq 1.5 m_{SF}, \quad m_{SF} \simeq 3 m_{\nu\text{MSM}}.$$

H J de Vega, N Sanchez, Phys. Rev. D85, 043517 (2012).

Sterile neutrino models

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- 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.
- χ -model (1981)-(2006) sterile neutrinos produced by a Yukawa coupling from a real scalar χ .
- Further models must reproduce $\bar{\rho}_{DM}$, galaxy and structure formation and be consistent with particle physics experiments.

WDM decoupling out of equilibrium behave approximately as particles decoupling at equilibrium but with a larger

mass: $m_{DW} \simeq 4.4 (m_{Thermal})^{4/3}$, $m_{SF} \simeq 3 m_{\chi}$, $m_{DW} \simeq 1.5 m_{SF}$. Linear information: $\bar{\rho}_{DM}$ and free-streaming length.