ΛWDM :*Galaxy Formation in Agreement with Observations*

Norma G. SANCHEZ

LERMA Observatoire de Paris & CNRS

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Usually, (littérature, conferences…), CDM is « granted » as « the » DM . And wimps as « the » DM particle.

In most work on CDM galaxies and galaxy formation simulations, the problems to agree with observations lead to cyclic CDM crisis, with more epicyclic type of arguments and recipes. Each time CDM is in trouble, recipes to make it alive for a while are given and so on. CDM galaxy formation turns around this situation from more than 20 years. The subject is turning around around itself.

(Moreover, such crisis led to wrongly replace DM by replacing laws of physics….) .

While on the past 20 years, cosmology, early and late universe, inflation, CMB , LSS, SSS, made progress and clarifications, Galaxy formation becames an increasingly « Ptolomeic » subject , a list of recipes or ad hoc prescriptions, « termed «astrophysical solutions » or « baryonic solutions » to CDM which exited from a scientific physical framework…. Namely, in CDM dominated galaxies, baryons,complexes environments and feedbacks need to make all the work…!!). CDM is the wrong solution to Galaxies and its Formation.

HIGHLIGHTS

(0)The Standard Model of the Universe Includes Inflation

(I) LATEST PREDICTIONS :

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

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

Clarification and Simplification

GALAXY FORMATION IN AGREEMENT WITH OBSERVATIONS

Analytical Results and Numerical (including analytical) Results

Basement- ground Zero

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

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. D85, 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. D85, 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.

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

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 loose energy radiating, it can fall deeper than if it cannot radiate.

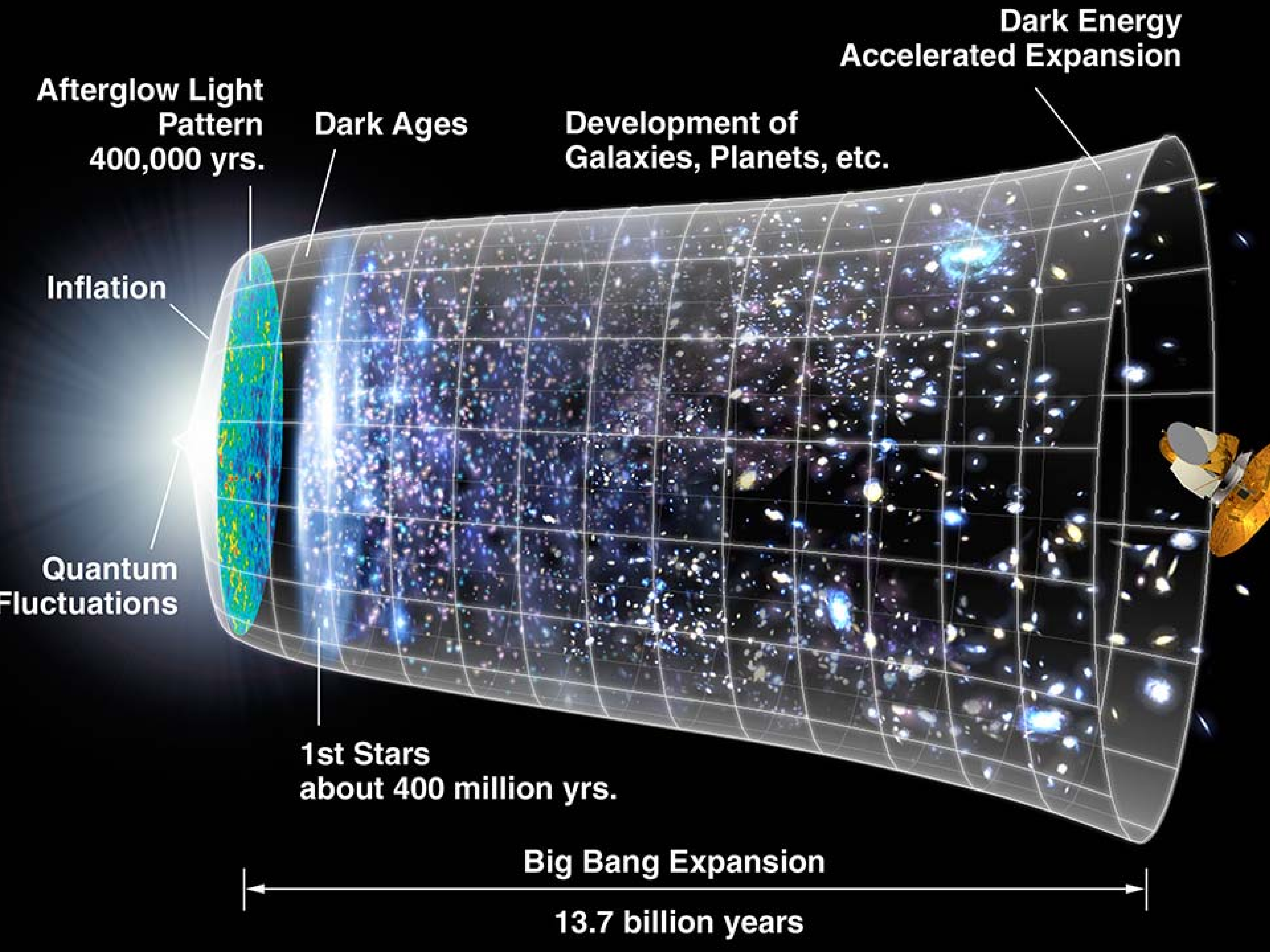
Standard Cosmological Model: ΛCDM $\Rightarrow$ ΛWDM

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

Standard Cosmological Model: DM + Λ + Baryons + Radi

- 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.


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Quantum Fluctuations During Inflation and after

The Universe is homogeneous and isotropic after inflation thanks to the fast and gigantic expansion stretching lenghts 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:

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

$M_{Planck} \gtrsim 10^{18}$ GeV $> \lambda^{-1}_{begin\,inflation} > 10^{14}$ GeV.

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

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

Universe expansion classicalizes the physics: decoherence

THE ENERGY SCALE OF INFLATION IS THE

THE SCALE OF GRAVITY IN ITS SEMICLASSICAL REGIME

(OR THE SEMICLASSICAL GRAVITY TEMPERATURE)

(EQUIVALENT TO THE HAWKING TEMPERATURE)

The CMB allows to observe it
(while is not possible to observe for Black Holes)

The Theory of Inflation

Inflation can be formulated as an effective field theory in the Ginsburg-Landau sense. Main predictions:

- The inflation energy scale turns to be the grand unification energy scale: $= 0.70 \times 10^{16}$ GeV
- The MCMC analysis of the WMAP+LSS data combined with the effective theory of inflation yields: a) the inflaton potential is a double–well, b) the ratio r of tensor to scalar fluctuations. has the lower bound: $r > 0.023 \; (95\% \; \mathrm{CL}) \quad , \quad r > 0.046 \; (68\% \; \mathrm{CL})$ with $r \simeq 0.051$ as the most probable value.

This is borderline for the Planck satellite ($\sim 12/2012?$)
Burigana et. al. arXiv:1003.6108, ApJ to appear.
D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sánchez, (review article), arXiv:0901.0549, Int.J.Mod.Phys.**A 24**, 3669-3864 (2009).

Two key observable numbers :

associated to the primordial density and primordial gravitons :

$$n_s = 0.9608 \,, \quad r$$

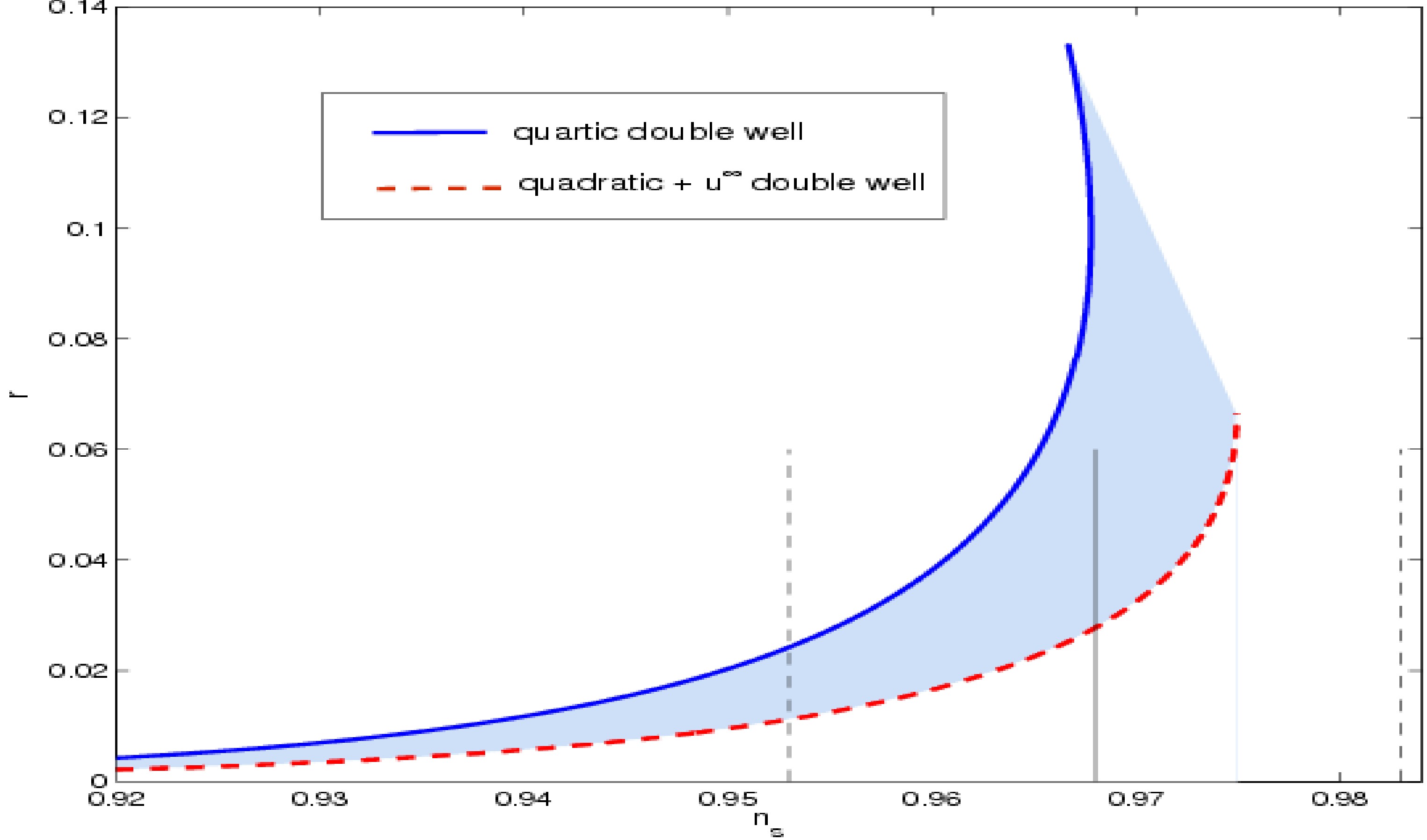
PREDICTIONS

$r < 0.053$

$r > 0.021$

$$0.021 < r < 0.053$$

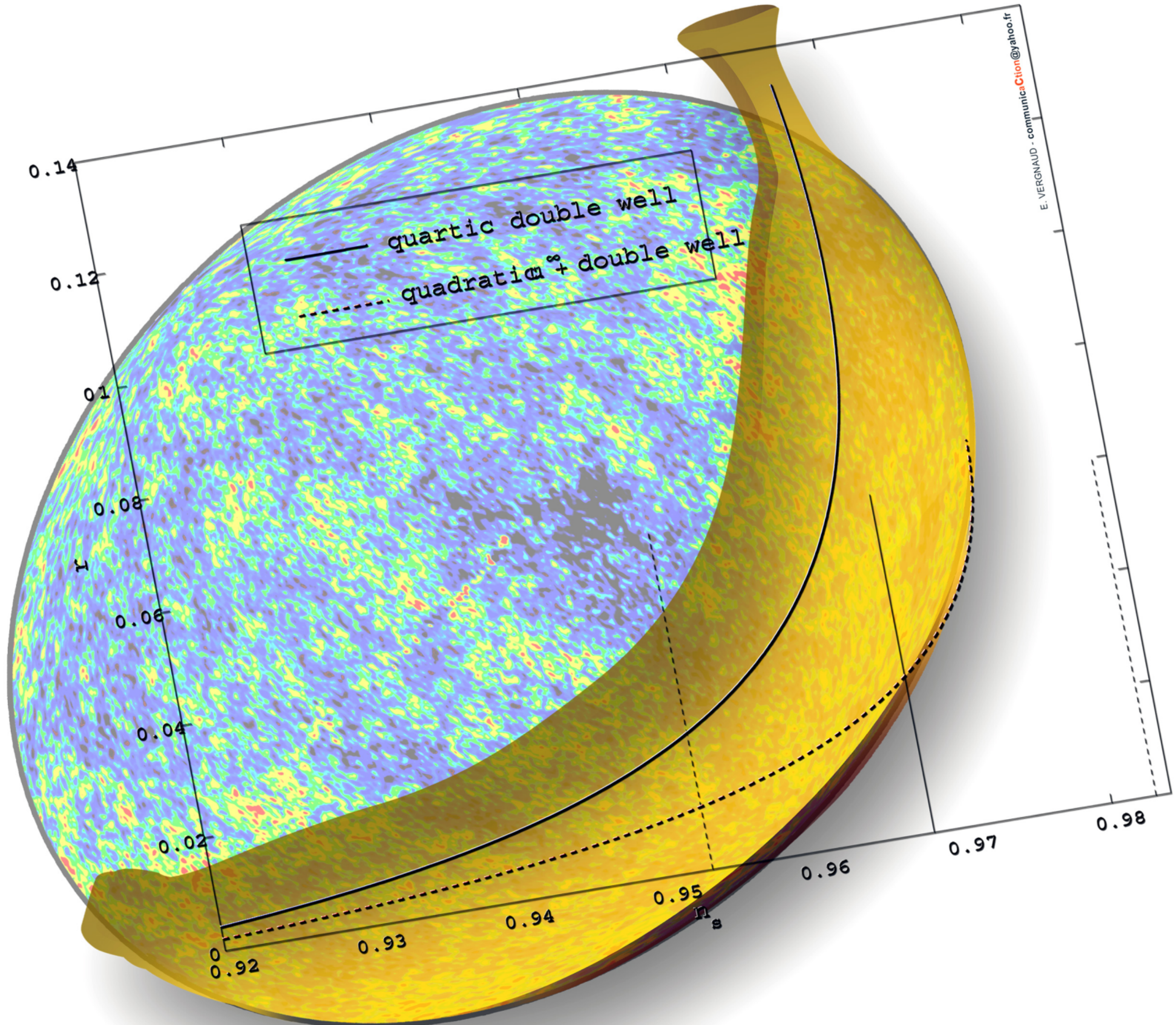
Most probable value: $r \sim 0.051$



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)


quartic double well
double well
r
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.92
0.93
0.94
0.95
0.96
0.97
0.98
n s
E. VERGNAUD - communicaCtion@yahoo.fr

PREDICTIONS From the cosmic banana:

UPPER BOUND $r < 0.053$

LOWER BOUND $r > 0.021$

$$0.021 < r < 0.053$$

Most probable value: $r \sim 0.051$

FORECASTS FOR PLANCK

With Fiducial $r = 0.0427$ • **We found for r at 95% CL:**

$$0.028 < r < 0.116$$

with the best values $r = 0.04$, $n_S = 0.9608$

C. Burigana, C. Destri, H.J. de Vega, A.Gruppuso, N. Mandolesi, P. Natoli, N. G. Sanchez :

ApJ 724, 588-607 (2010)

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:

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

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 $m \sim$ keV WDM particles $r_{lin} \sim 60$ 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).

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:

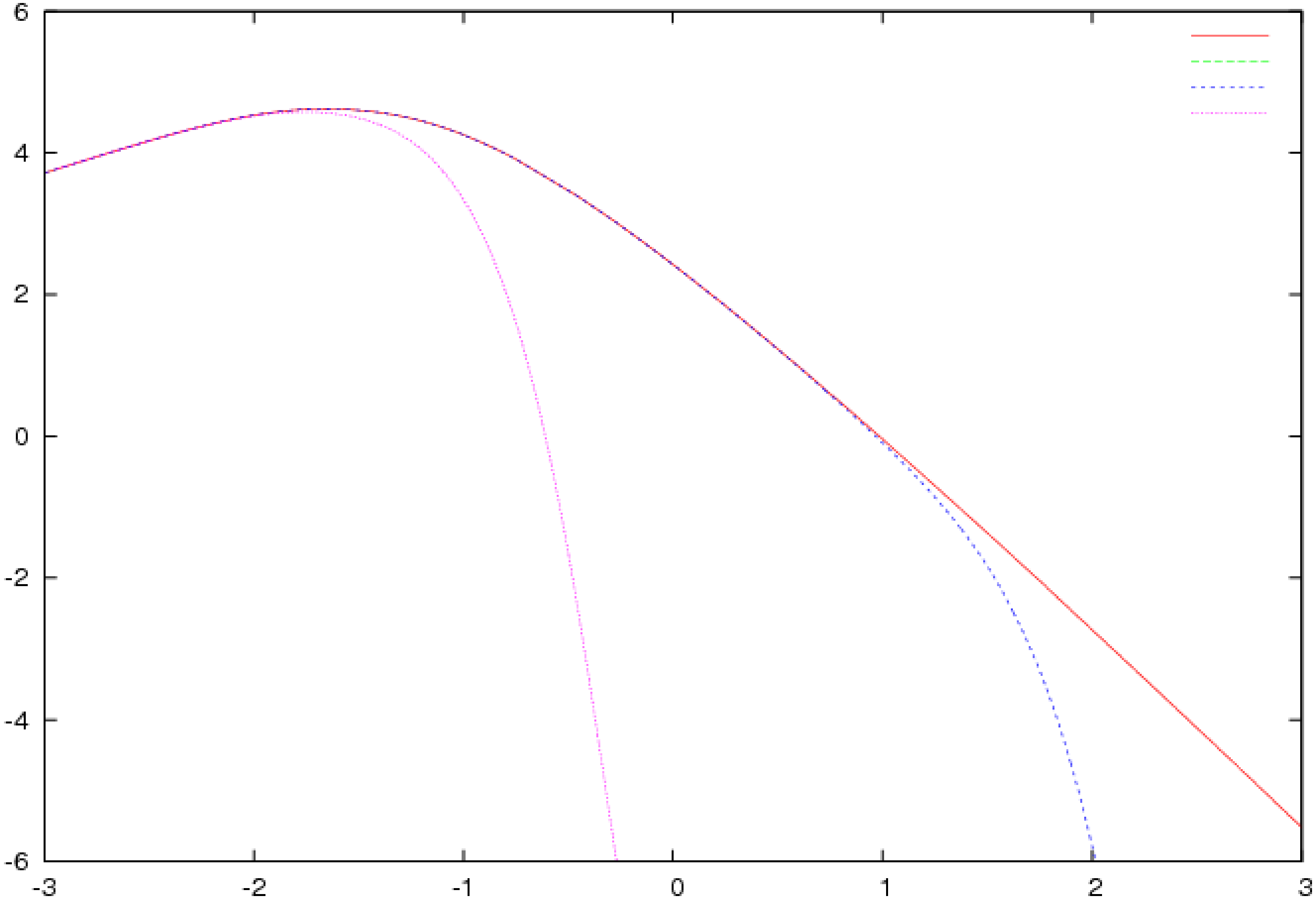
CMB + LSS + SSS Observations

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

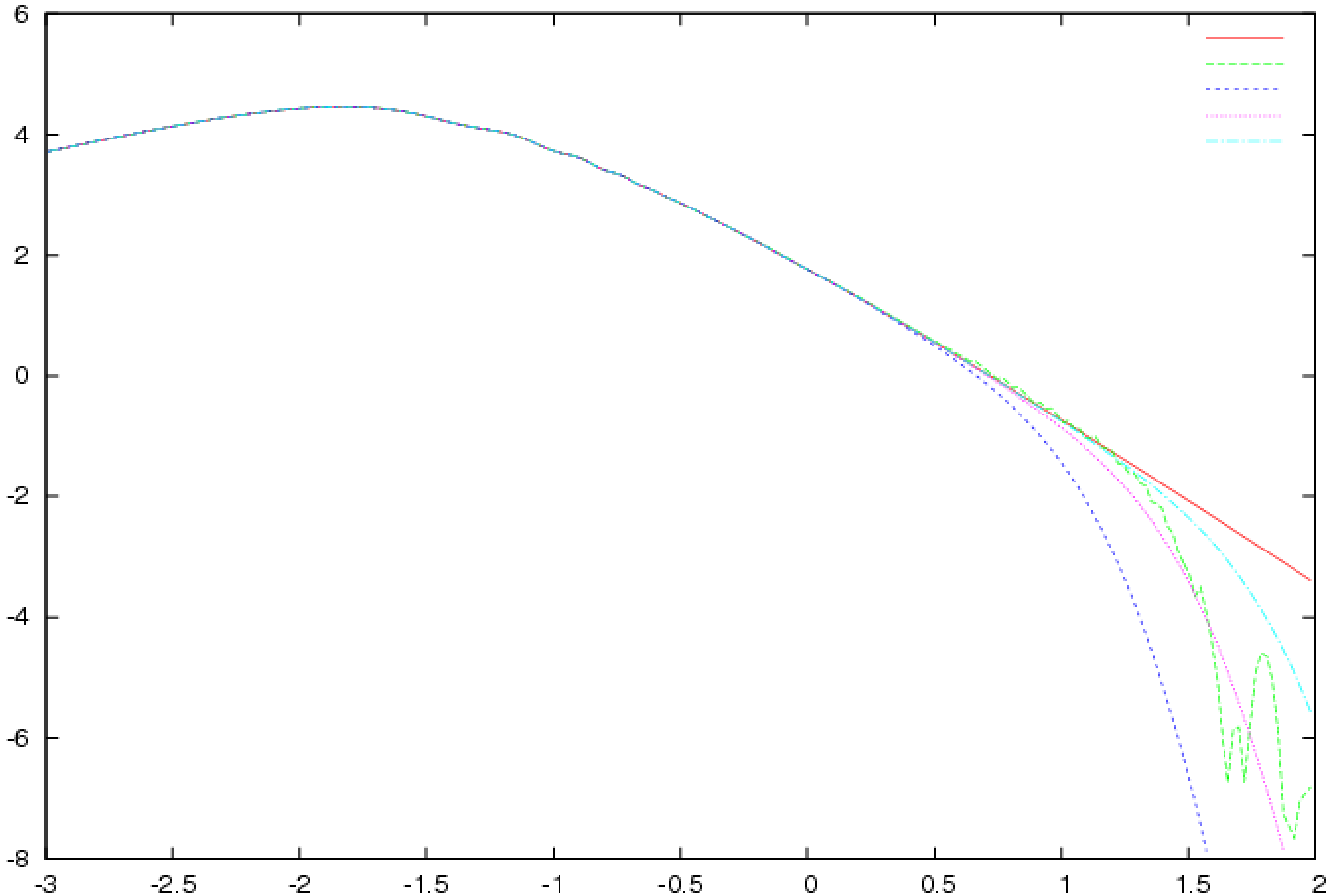


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS, 1 keV DM particles and 10 eV DM particles. $P(k) = P_0\, k^{n_s}\, T^2(k)$.

$P(k)$ 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



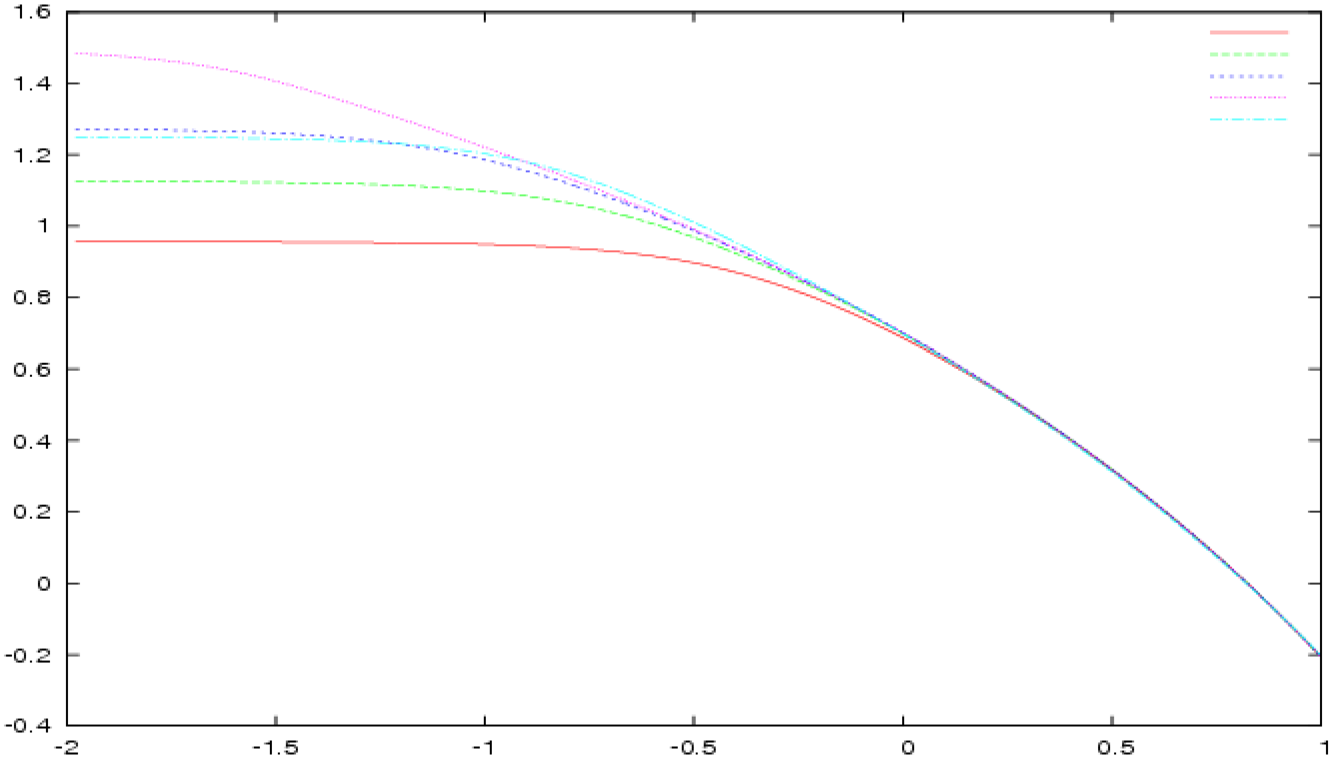
$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for CDM, 1 keV, 2 keV, light-blue 4 keV DM particles decoupling in equil, and 1 keV sterile neutrinos. WDM cuts $P(k)$ on small scales

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

The expected overdensity

The expected overdensity within a radius R in the linear regime

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

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

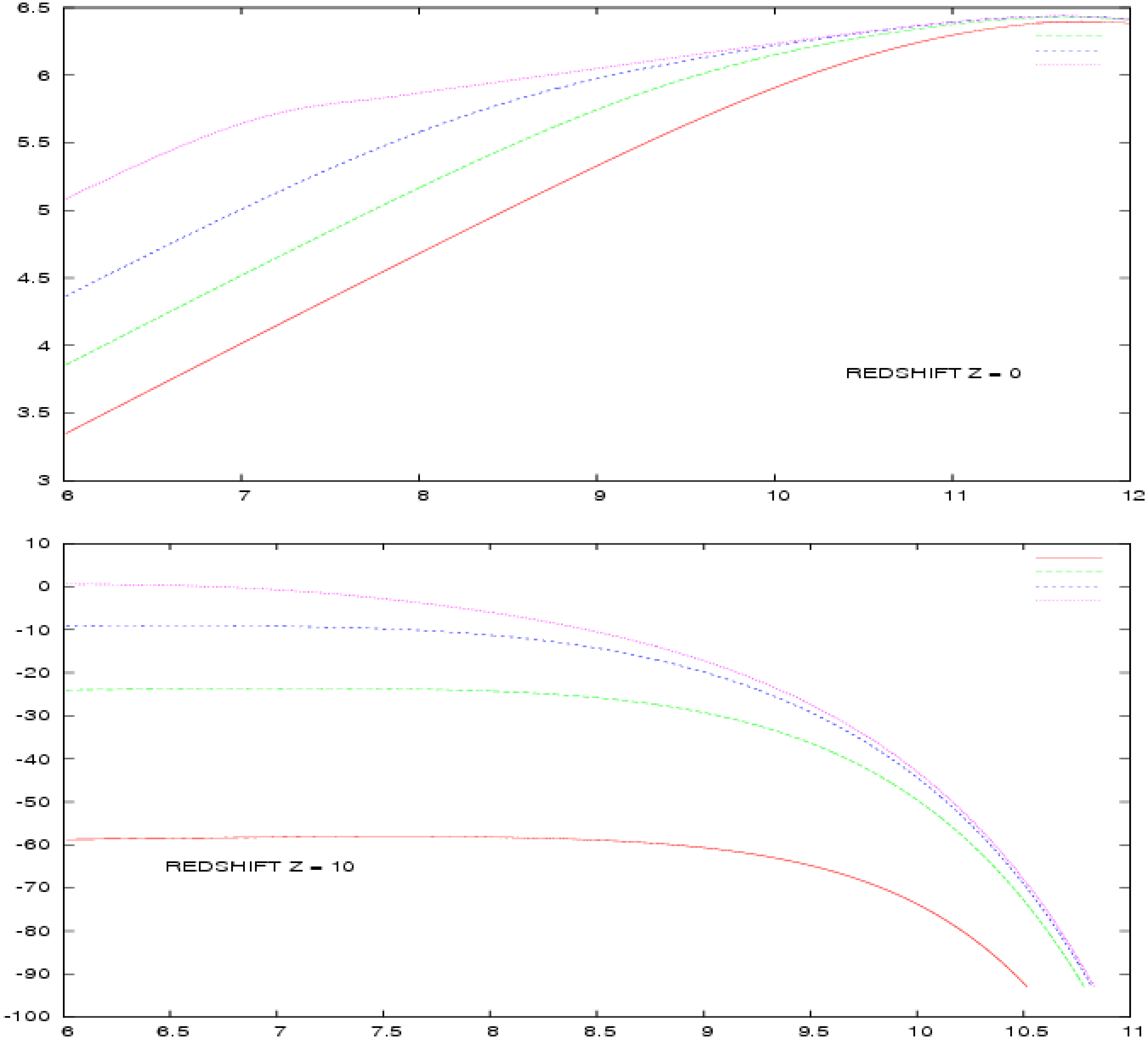
$\delta_c = 1.686\ldots$: linear estimate for collapse from the spherical model.

$\sigma(M, z)$ is constant for WDM for small scales: small objects (galaxies) formation is suppresed 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, $g(0) = 0.76\ ,\ \ g(\infty) = 1$

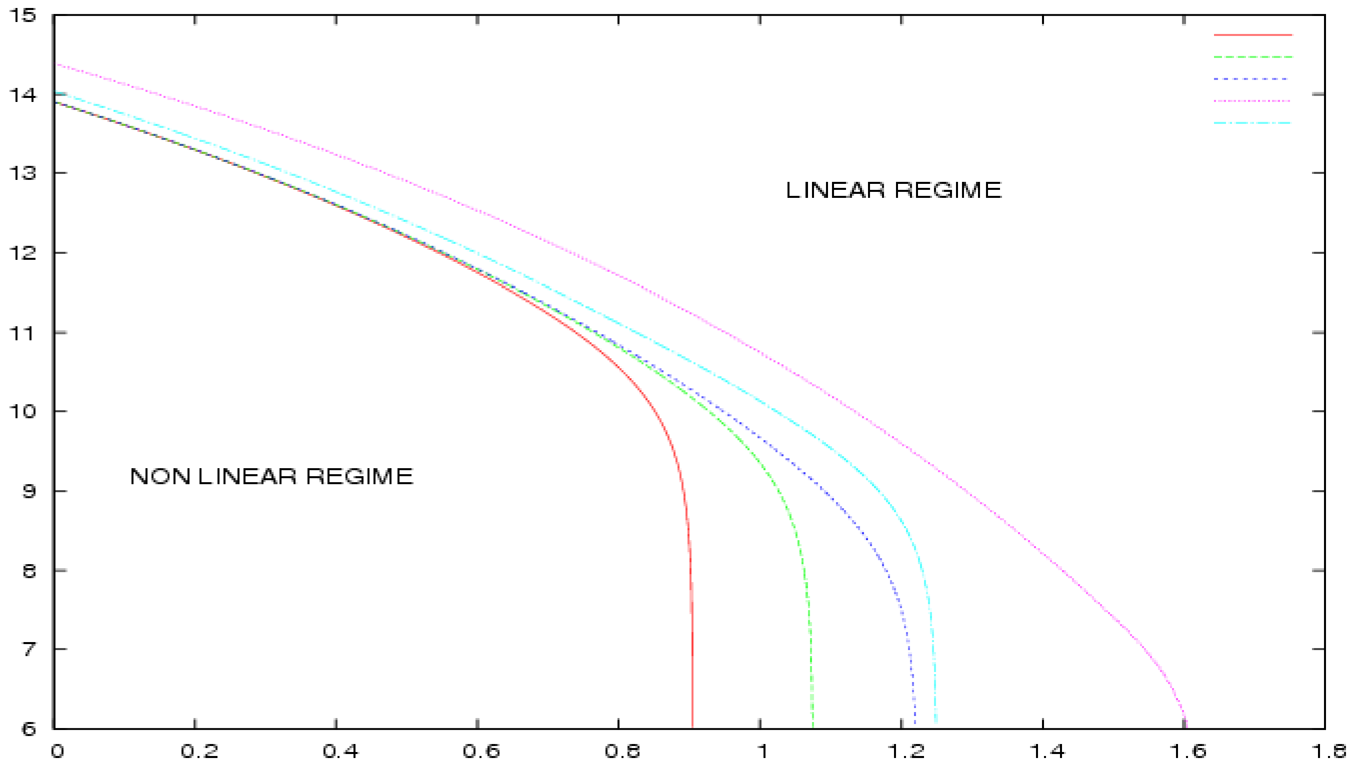
$(M^2/\rho) \log d\sigma(M,z)/d\ln M$ **vs.** $\log_{10} M/M_\odot$



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

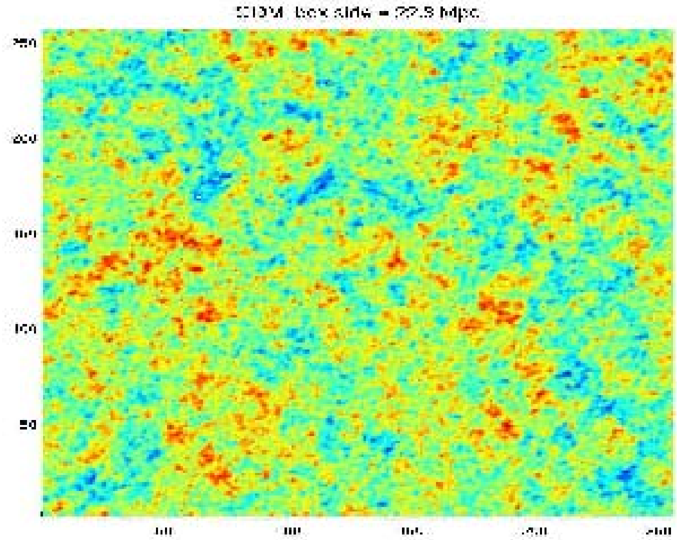
Linear and non-linear regimes in z and R

$\sigma^2(R,z) \sim 1$: 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.



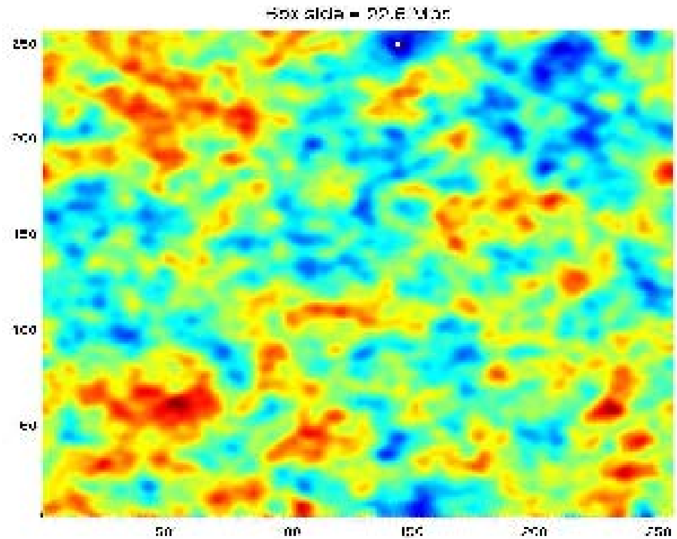
$\log M/M_\odot$ vs. $\log(z+1)$ for CDM, 1 keV, 2 keV, 4 keV DM particles decoupling in equil, and 1 keV (light-blue) sterile ν.

WDM vs. CDM linear fluctuations today

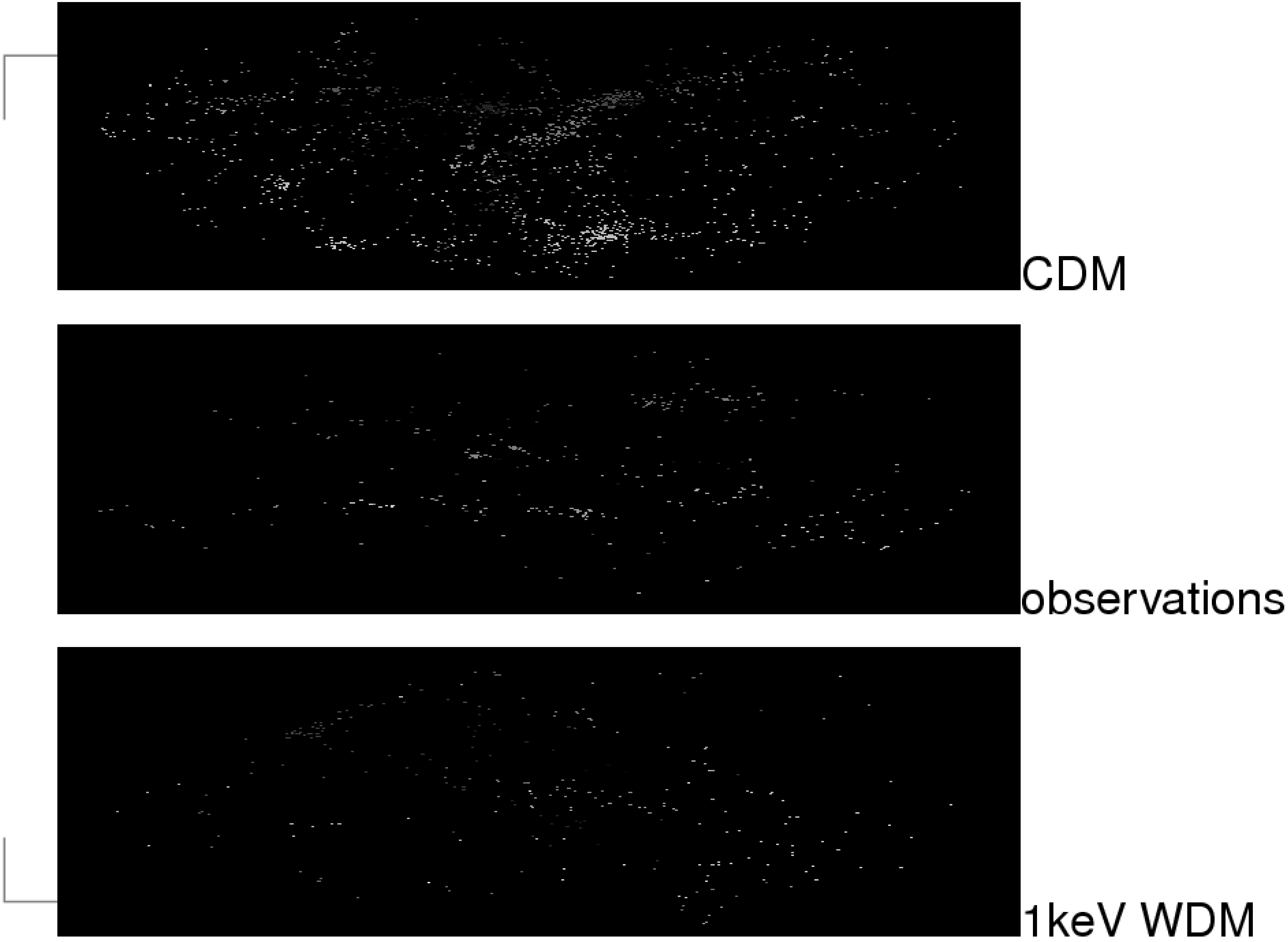


Box side = 22.6 Mpc. [C. Destri, private communication].

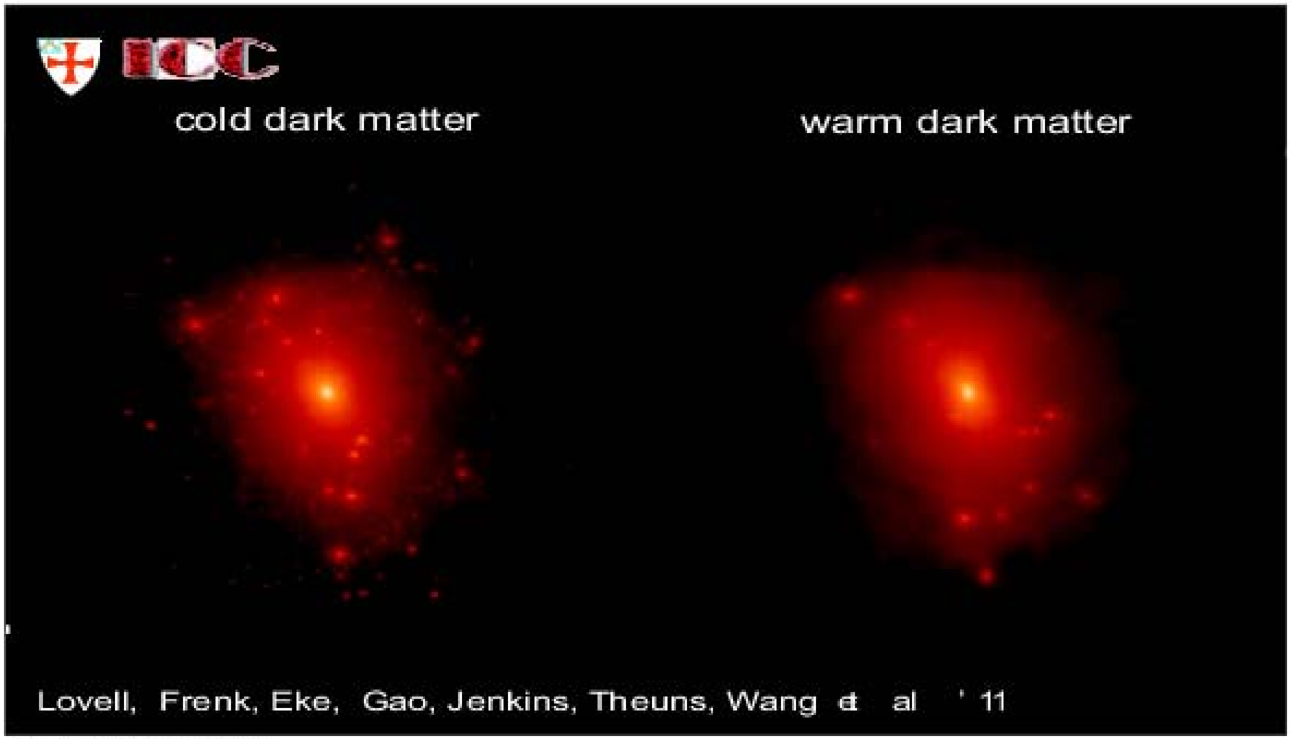
WDM:



ΛCDM and ΛWDM simulations vs. astronomical observat



N-body WDM Simulations



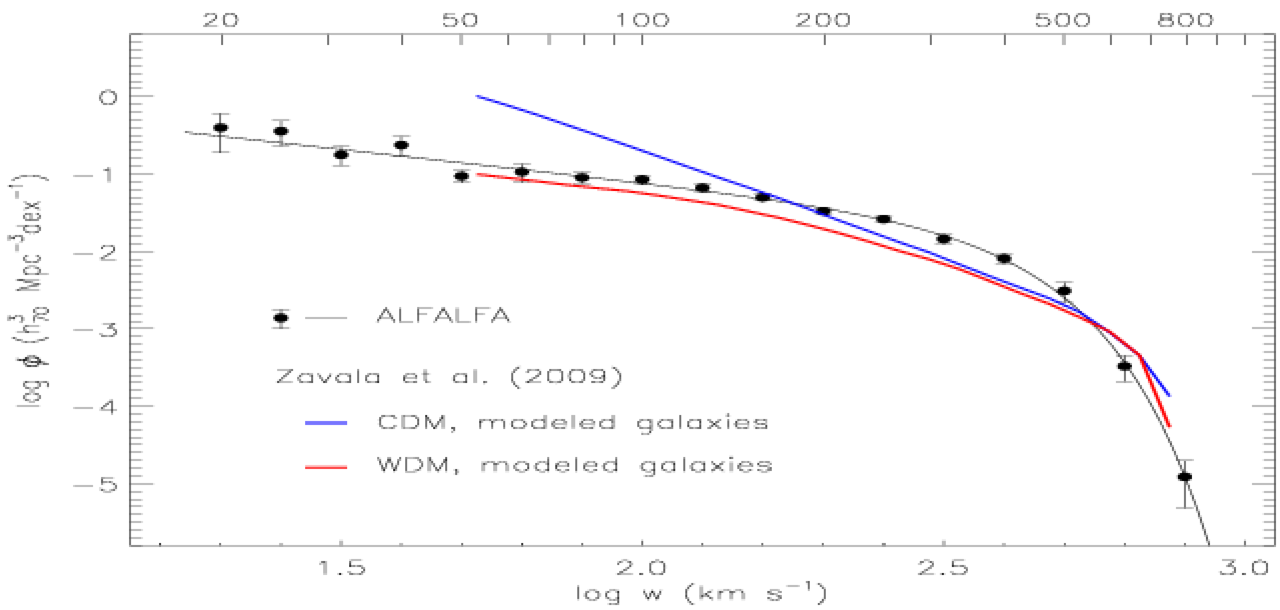
Wednesday, 15 June 2011

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 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)=

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

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 $\equiv R_{virial}/r_0$. CDM concentrations disagree with observed

keV SCALE DARK MATTER PARTICLES REPRODUCE:

→OBSERVED GALAXY DENSITIES AND VELOCITY DISPERSIONS

→OBSERVED GALAXY CORED DENSITY PROFILES

->OBSERVED SURFACE DENSITY VALUES OF DARK MATTER DOMINATED GALAXIES

→SOLVES the OVERABUNDANCE (“satellite) PROBLEM and the CUSPS vs CORES Problem

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

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

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

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

→Compilation of observations of galaxies candidates for DM structure, are compatible with a core of smooth central density and a low mean mass density ~ 0.1 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 ~ 2 – 3 kpc.

→In addition, the decoupling can occurs at local thermal equilibrium or out of local thermal equilibrium. All these cases have been considered in 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 $\langle\sigma^2_{DM}(t)\rangle$.

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

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

I_2 and I_4 are momenta of the DM distribution function.
g : $\#$ of internal degrees of freedom of the DM particle, $1 \leq g \leq 4$.

Mass Estimates for DM particles

Combining the previous expressions lead to general formulas for m and g_d:

$$m = 0.2504\,\mathrm{keV}\ \left(\frac{Z}{g}\right)^{\frac{1}{4}} \frac{\left[\int_0^\infty y^4\ F_d(y)\ dy\right]^{\frac{3}{8}}}{\left[\int_0^\infty y^2\ F_d(y)\ dy\right]^{\frac{5}{8}}}$$

$$g_d = 35.96\, Z^{\frac{1}{4}}\ g^{\frac{3}{4}}\ \left[\int_0^\infty y^4\ F_d(y)\ dy\ \int_0^\infty y^2\ F_d(y)\ dy\right]^{\frac{3}{8}}$$

These formulas yield for relics decoupling UR at LTE:

$$m = \left(\frac{Z}{g}\right)^{\frac{1}{4}}\ \mathrm{keV} \left\{ \begin{array}{l} 0.568 \\ 0.484 \end{array} \right. ,\ g_d = g^{\frac{3}{4}}\ Z^{\frac{1}{4}} \left\{ \begin{array}{ll} 155 & \text{Fermions} \\ 180 & \text{Bosons} \end{array} \right. .$$

Since $g = 1-4$, we see that $g_d > 100 \Rightarrow T_d > 100$ GeV.

$1 < Z^{\frac{1}{4}} < 5.6$ for $1 < Z < 1000$. Example: for DM Majorana fermions $(g = 2)$ $m \simeq 0.85$ keV.

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, $(Z > 1)$: $\quad Q_{today} = \frac{1}{Z}\, Q_{prim}$

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.

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:

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

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: keV $\lesssim m \lesssim$ 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.

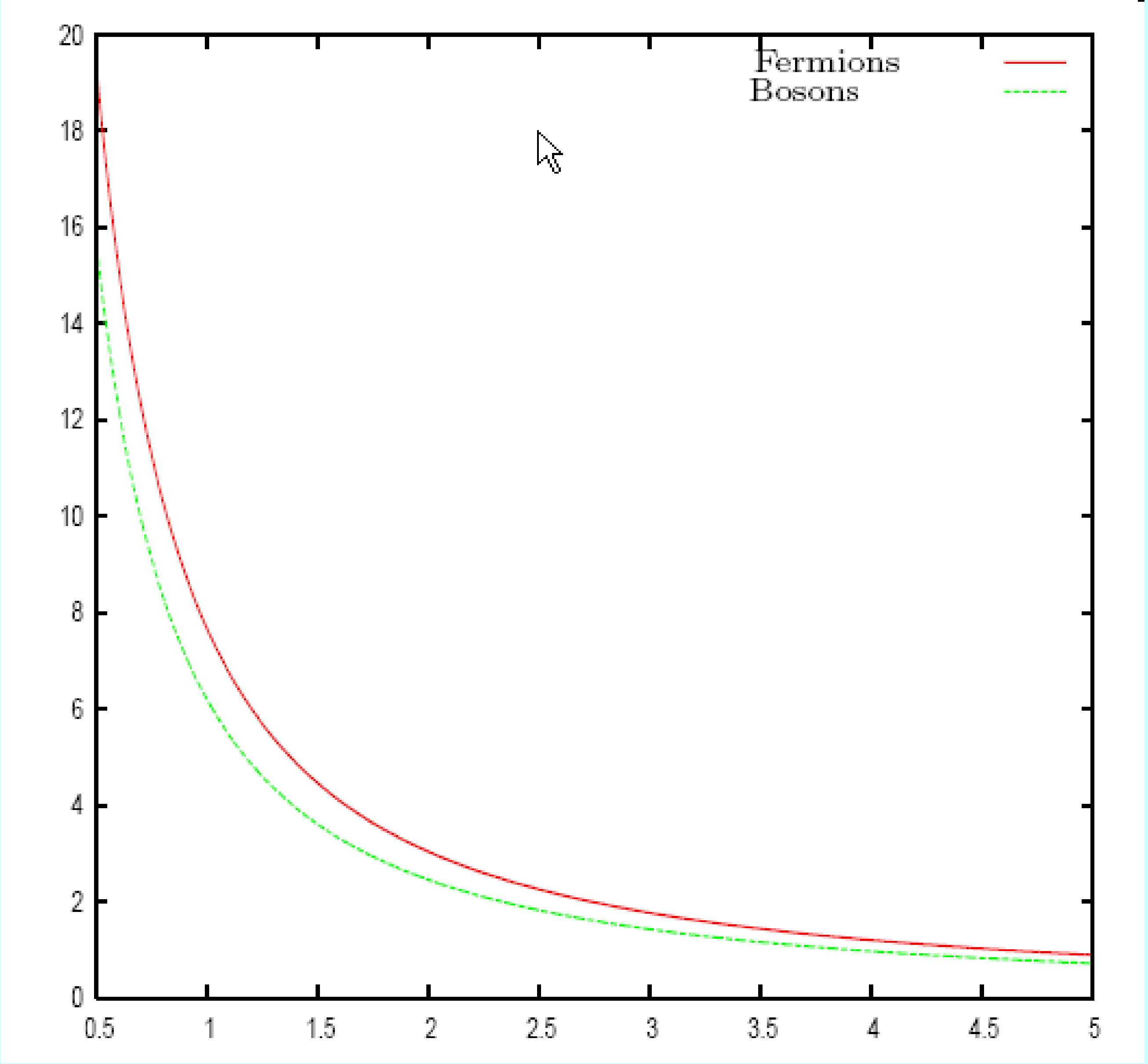
- The comoving **Jeans' (free-streaming) wavelength,** ie the largest wavevector exhibiting gravitational instability , and **the Jeans' mass** (the smallest unstable mass by gravitational collapse) are obtained in the range

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

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

- 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 $10^{12}\ M_{sun}$ and the comoving free-streaming length is of the order of the galaxy sizes today ~ 100 kpc



The free-streaming wavelength today in kpc vs. the dark matter particle mass in ke
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 σ_0 : $\sigma_0 >$ $(0.239 - 0.956)\ 10^{-9}\ \mathrm{GeV}^{-2}$ and $\sigma_0 < 3200\ m\ \mathrm{GeV}^{-3}$. 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 GeV and T_d = 5 GeV would require a huge $Z \sim 10^{23}$, well above the upper bounds obtained and cannot reproduce the observed galaxy properties.

Wimps produce extremely short free-streaming or Jeans length today $\lambda_{fs}(0) = 3.51\ 10^{-4}$ pc = 72.4 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, $10^{12}\ M_{sun}$.

(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:

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

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 galax

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, $\rho_0 =$ central density for DM galaxies

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

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 $\mu_{0D} \simeq 80 \, \frac{M_\odot}{\mathrm{pc}^2}$ in interstellar molecular clouds of size r_0 of different type and composition over scales $0.001 \, \mathrm{pc} < r_0 < 100 \, \mathrm{pc}$ (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

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

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:

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

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

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

Linear density profile

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

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

The linear profile today results:

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

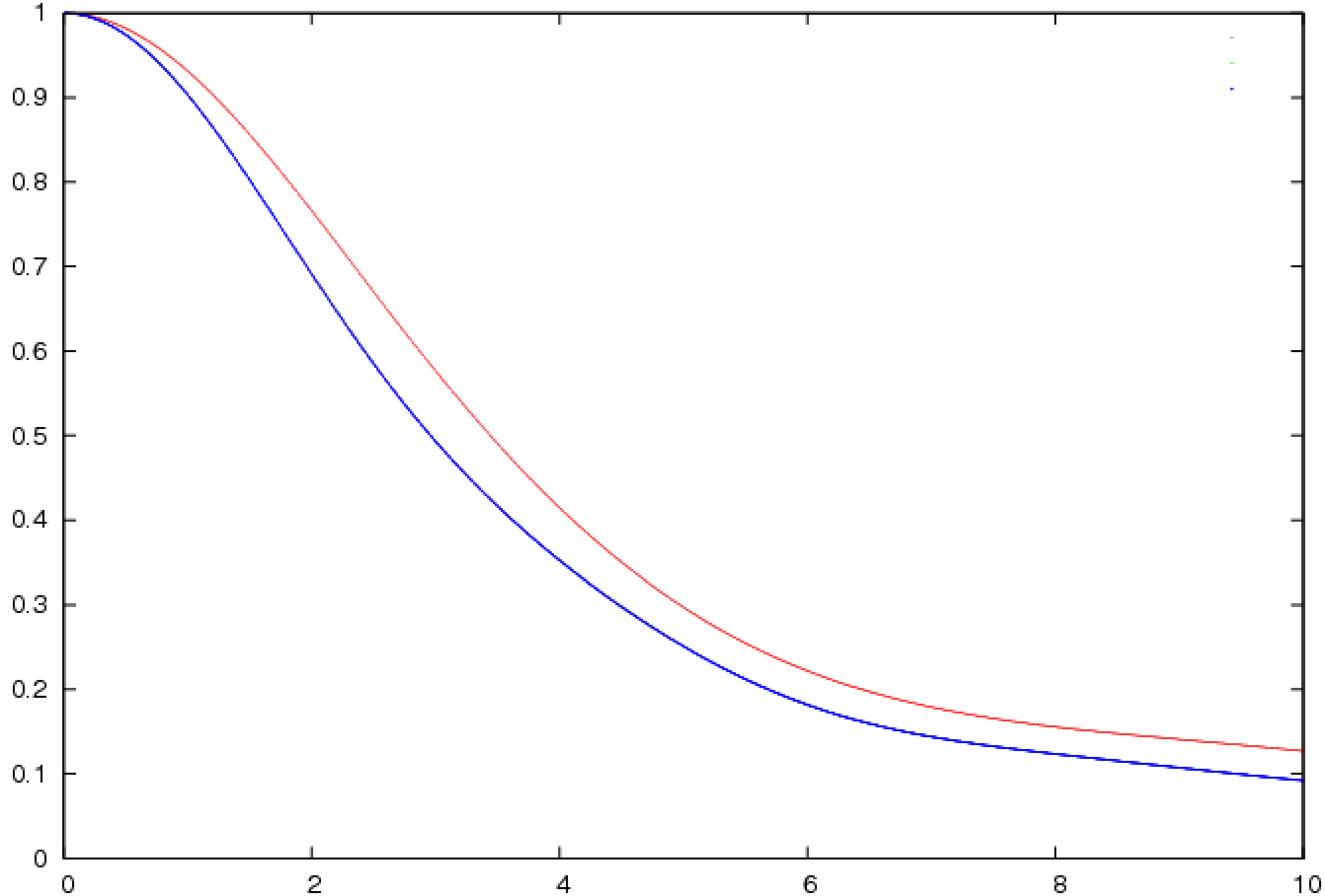
where $\gamma \equiv k\,r_{lin}$ and $x \equiv r/r_{lin}$.

I_n and $\bar{\Delta}(z,\gamma)$ depend on the freezed-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 $r \gtrsim r_{lin}$:

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

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

The theoretical linear results agree with the universal empirical behaviour $r^{-1.6\pm0.4}$: M. G. Walker et al. (2009) (observations), I. M. Vass et al. (2009) (simulations).

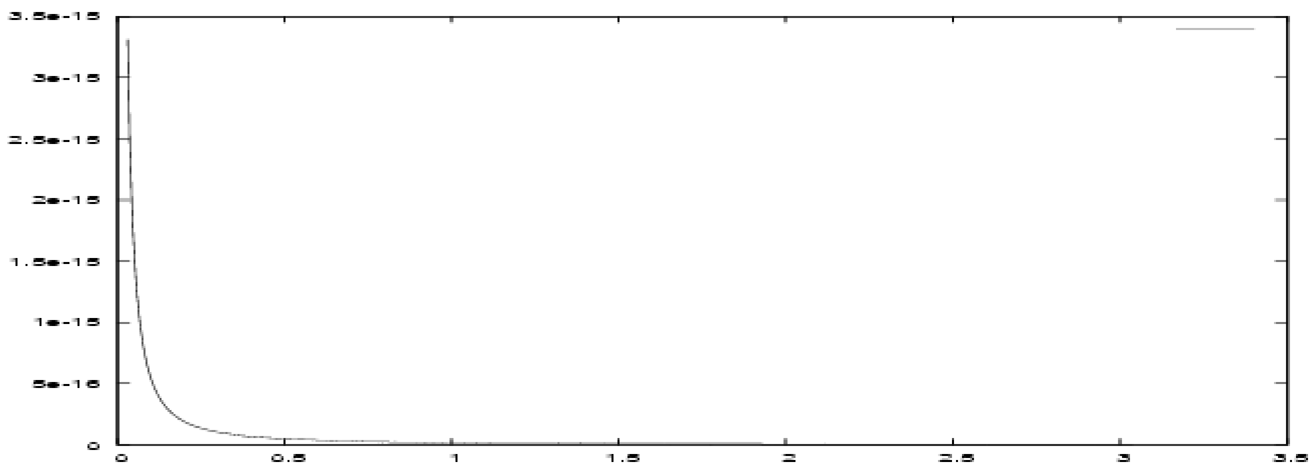
The agreement between the linear theory and the observations is remarkable.

In the asymptotic regime $r \gg r_{lin}$ the small k behaviour of $\Delta(k, t_{\text{today}}) \overset{k\to 0}{=} c_1 \, (k \, r_{lin})^s$ with $s \simeq 0.5$ implies the presence of a tail: $\rho_{lin}(r) \overset{r \gg r_{lin}}{\simeq} c \left(\frac{r_{lin}}{r}\right)^2$.

Wimps vs. galaxy observations

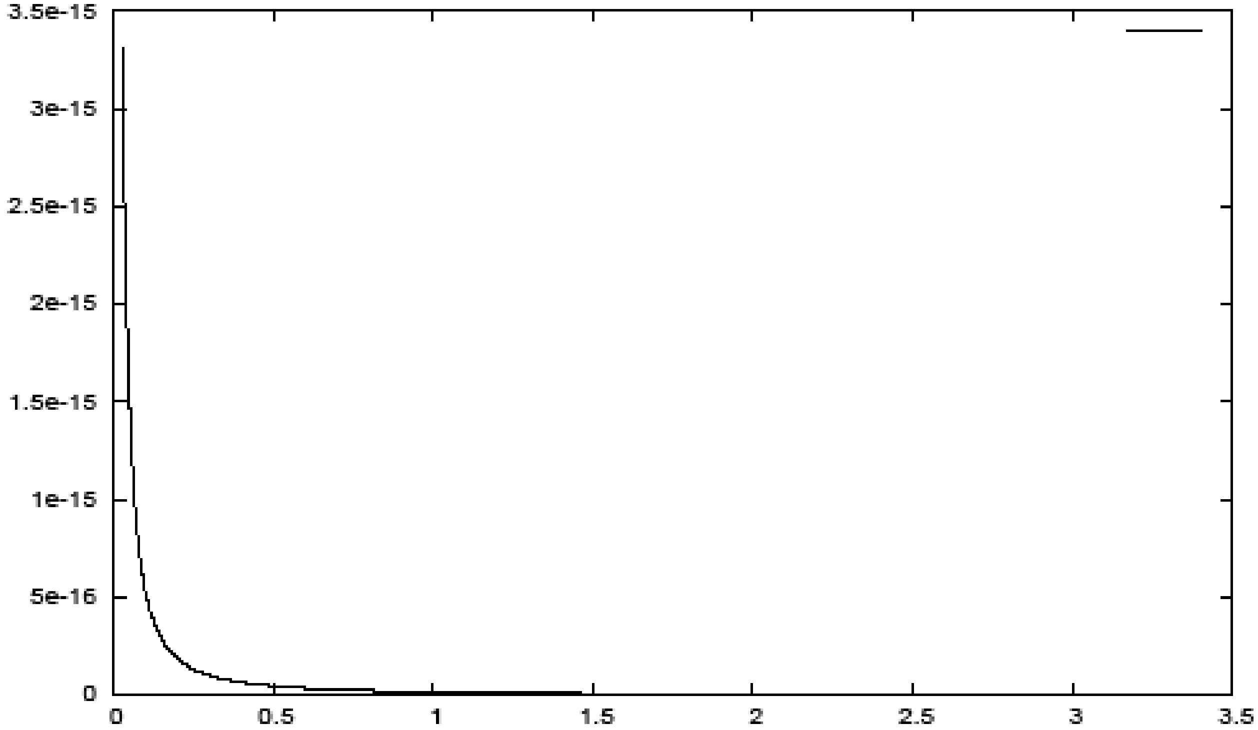
	Observed Values	Wimps in linear theory
r_0	5 to 52 kpc	0.045 pc
ρ_0	1.57 to $19.3 \times 10^{-25} \ \frac{\mathrm{g}}{\mathrm{cm}^3}$	$0.73 \times 10^{-14} \ \frac{\mathrm{g}}{\mathrm{cm}^3}$
$\sqrt{v^2}_{halo}$	79.3 to 261 km/sec	0.243 km/sec

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 $r \gtrsim 0.03$ 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)=

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 $\equiv R_{virial}/r_0$. 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:

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

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

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

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

Conclusion: r_q is in the parsec range for WDM $m \sim$ 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

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

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

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

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

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

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

Equilibrium: $P_q = P_G \Longrightarrow M_q = \dfrac{9}{2\,\sqrt{\pi}\, m^2}\, \left(\frac{\hbar\, v}{G}\right)^{\frac{3}{2}} =$

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

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

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

elf-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 $\Longrightarrow \frac{d\mu}{dr}(0) = 0$.

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

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

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

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

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

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

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

Thomas-Fermi approximation: solutions

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

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

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.

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).

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 $\mu_0 \simeq (18 \, \mathrm{MeV})^3$ 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 $m_{DM} \sim$ 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?

(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

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 ciclic 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 ("adiabatic contraction", non circular motions, triaxiality, mergers, over increased baryon and supernovae 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 candidats (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 plugged 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).

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 DIFFEREN 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)

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:

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

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

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.
- 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.

The number of observed Milky-Way satellites indicates lower bounds between 2 keV and 13 keV for different models of sterile neutrinos.

keV sterile neutrino WDM in minimal extensions of the Standard Model is consistent with Lyman-alpha constraints within a wide range of the model parameters.

Lyman-alpha observations give a lower bound for the sterile neutrino mass of 4 keV only for sterile neutrinos produced in the case of a non-resonant (Dodelson-Widrow) mechanism.

The Lyman-alpha lower bounds for the WDM particle mass are smaller in the Neutrino Minimal Standard Model (sterile neutrinos produced by the decay of a heavy neutral scalar) and for fermions in thermal equilibrium.

Warm Dark Matter keV sterile neutrino

It is well known that dark matter (DM) is not described by the Standard Model (SM) of particle physics.

Many extensions can be envisaged to include DM particles, coupled weakly enough to the SM particles to fulfill all particle experimental constraints, namely the fact that DM has not been detected so far in any particle physics experiment.

On the other hand, cosmological and astrophysical constraints such as the ones coming from the dark matter density and the galaxy phase space density, or alternatively, the universal galaxy surface density, lead to DM candidates in the keV mass scale, namely Warm DM (WDM

A keV mass scale sterile neutrino is the front running candidate for WDM.

Other WDM candidates in the keV mass scale are: gravitinos, light neutralino and majorons

Detection of massive neutrinos by β-decay

KATRIN has the potential to detect sterile neutrinos with mass up to 18keV.

- **WDM Sterile neutrinos can be naturally embedded in the SM of particle physics.**

- **They do not participate in weak interactions, and hence they are singlets of color, weak SU(2) and weak hypercharge.**

- **One sterile neutrino per lepton family is expected, but only the lightest one (i.e. electron family) has a life time of the order of Hubble time and can describe the DM.**

- **Consider Rhenium 187 and Tritium beta decay experiments to detect a keV mass sterile neutrino as a DM candidate:**
- **will be a mixing of two mass eigenstates:**
- **one light active neutrino and one keV scale sterile neutrino mass state**

- **Sterile neutrinos in the beta decay of Rhenium 187 are currently searched by the Microcalorimeter Arrays for a Rhenium Experiment (MARE). In this decay the available energy is Q(187Re) ~ 2.47 keV.**

- **Beta decay of Rhenium 187 into Osmium 187**

- **Up to now, the no observation of keV scale sterile neutrinos in the**
- **beta decay of Rhenium 187 gave an upper bound**

  on the mixing angle $\zeta < 0.095$ for 1 keV steriles,

- **which is compatible with the cosmological constraints on the mixing angle,**
- **$\zeta \sim 10^{-4}$,**
- **appropriate to produce enough sterile neutrinos to account for the observed DM.**

- **Remind : the amount of the sterile neutrinos that could be produced in the early universe also depends on the production mechanism which is model dependent.**

- **The Karlsruhe Tritium Neutrino Experiment (KATRIN) is currently studying the Tritium beta decay [and, if suitably adapted, it could show the presence of a sterile neutrino as well].**

In this decay the available energy is Q(3H1) ~ 18.6 keV.

The beta decay of Tritium into Helium 3 is an allowed transition (1/2+ → 1/2+) with Fermi

- **Theory combined with galaxy data indicates a DM particle mass m between 1 and 10 keV. This keV scale value is independent of the particle physics model.**

- **The number of Milky-Way satellites indicates lower bounds between 2 and 13 keV for different models of sterile neutrinos.**

- **Lyman-alpha constraints give a lower bound of**
- **m > 4 keV only for sterile neutrinos assuming a non-resonant Dodelson-Widrow production mechanism.**

- **The mixing angle theta between active and sterile neutrinos should be in the 10^{-4} scale to reproduce the average DM density in the Universe.**

- **Only a direct detection of the DM particle can give a clear-cut answer to the nature of DM and at present, only the KATRIN and MARE experiments have the possibility to do that for sterile neutrinos.**