Galaxy properties,

keV scale dark matter

and the power of linear approximation

Norma G. SANCHEZ

Observatoire de Paris & CNRS

[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 “WIMPS”) REVEALED SO FAR, UNSUCCESSFULL

BUT DARK MATTER DOES EXIST

IN DESPITE OF THAT: PROPOSALS TO REPLACE DARK MATTER DO APPEAR:

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 :BUILDING MODELS, DEDICATED LAB EXPERIMENTS, ANNHILATING DARK MATTER, (FULLY CONCENTRATED ON "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 NOT GOING WELL IN THE RESEARCH ON THE DARK MATTER SUBJECT

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

"FUIT EN AVANT" ("ESCAPE TO THE FUTURE") IS NOT THE ISSUE

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 "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)]

CONTENTS OF THIS LECTURE

(0) FRAMEWORK

(I) THE MASS OF THE DARK MATTER PARTICLE

(II) THE BOLTZMAN VLASOV EQUATION: TRANSFERT FUNCTION AND ANALYTIC RESULTS

(III) UNIVERSAL PROPERTIES OF GALAXIES: DENSITY PROFILES, SURFACE DENSITY, AND THE POWER OF LINEAR APPROXIMATION

(I) 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)**

(II) 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)**

(III) DENSITY PROFILES, SURFACE DENSITY, DARK MATTER PARTICLE MASS

H. J. De Vega, N.G. Sanchez ***On the constant surface density in dark matter galaxies and interstellar molecular clouds*** **arXiv:0907.006**

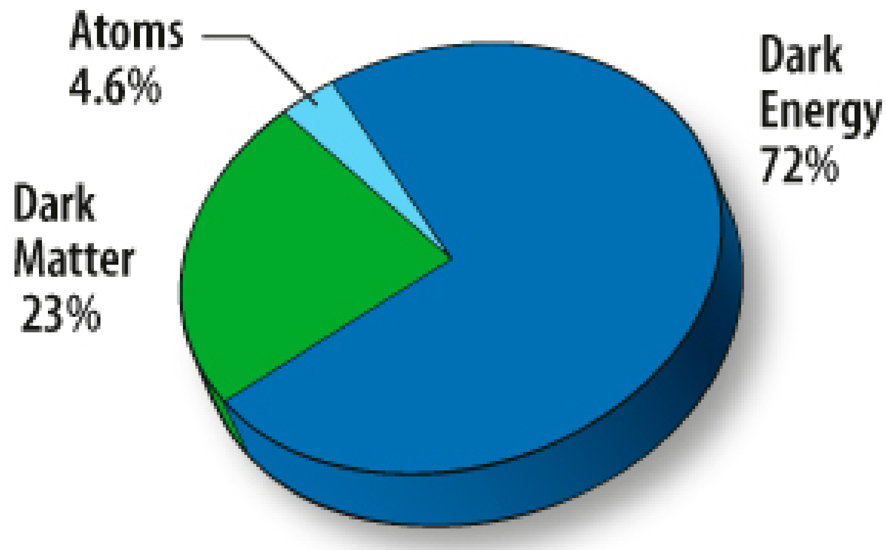
H. J. De Vega, P. Salucci, N.G. Sanchez ***Universal galaxy properties and the mass of the dark matter particle from theory and observations: the power of the linear approximation*** **arXiv:1004.1908**

Dark matter was noticed seventy-five years ago (Zwicky 1933, Oort 1940). Ist nature is not yet known. DM represents about 23.4 % of the matter of the universe. DM has only been detected indirectly through its gravitational action.

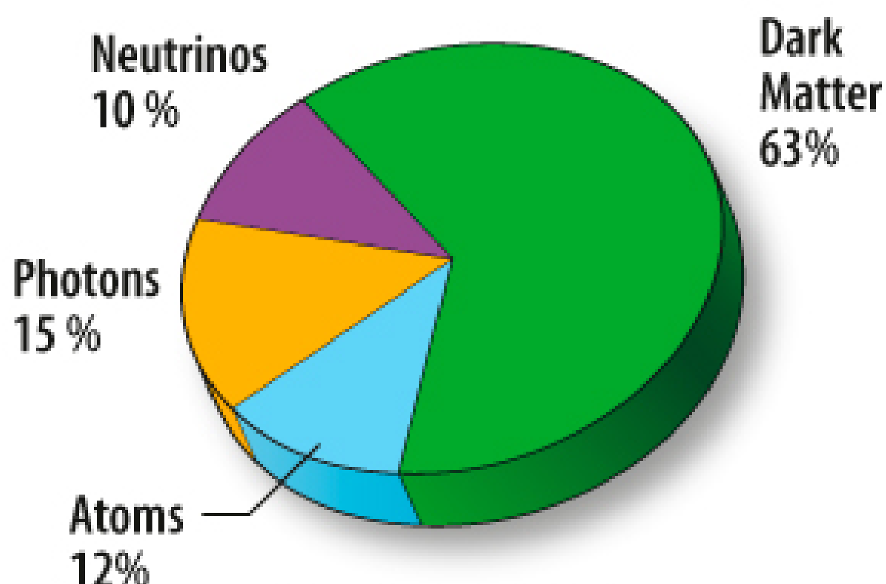
The concordance ΛCDM standard cosmological model emerging from the CMB and LSS observations and simulations favors dark matter composed of primordial particles which are cold and collisionless.

The clustering properties **of collisionless dark matter candidates in the linear regime depend on the free streaming length, which roughly corresponds to the Jeans length with the particle's velocity dispersion replacing the speed of sound in the gas.**

CDM candidates feature a small free streaming length favoring a bottom-up hierarchical approach to structure formation, smaller structures form first and mergers lead to clustering on the larger scales.



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Standard Cosmological Model: ΛCDM

ΛCDM = Cold Dark Matter + Cosmological Constant 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 (H_0) Measurements
- Properties of Clusters of Galaxies
- Measurements of the Age of the Universe

Standard Cosmological Model: ΛCDM

ΛCDM = Cold Dark Matter + Cosmological Constant

- 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.
- CDM: dark matter is cold (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.

(I) THE MASS OF THE

DARK MATTER PARTICLE

Compilation of observations of dSphs, prime candidates for DM subtructure, are compatible with a core of smoother 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 by the time of structure formation at $z < 30$ 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

→Compute 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 Td **are obtained.**

The phase-space density today is a factor Z smaller than its primordial value. The decreasing factor Z > 1 is due to the effect of non-linear self-gravity interactions: the range of Z is computed both analytically and numerically.

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 dwarf spheroidal satellite galaxies observations in the Milky Way 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 :

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

Dark Matter

DM must be non-relativistic by structure formation ($z < 30$) in order to reproduce the observed small structures at $\sim 2-3$ kpc. DM particles can decouple being ultrarelativistic (UR) at $T_d \gg m$ or non-relativistic $T_d \ll m$.
Consider particles that decouple at or out of LTE
(LTE = local thermal equilibrium).
Distribution function:
$f_d[a(t)\ P_f(t)] = f_d[p_c]$ freezes out at decoupling.
$P_f(t) = p_c/a(t) =$ Physical momentum.
$p_c =$ comoving momentum.

Velocity fluctuations: $y = P_f(t)/T_d(t) = p_c/T_d$

$$\langle \vec{V}^2(t) \rangle = \langle \frac{\vec{P}_f^2(t)}{m^2} \rangle = \frac{\int \frac{d^3P_f}{(2\pi)^3} \frac{\vec{P}_f^2}{m^2} f_d[a(t)\ P_f]}{\int \frac{d^3P_f}{(2\pi)^3} f_d[a(t)\ P_f]} = \left[\frac{T_d}{m\ a(t)}\right]^2 \frac{\int_0^\infty y^4 f_d(y) dy}{\int_0^\infty y^2 f_d(y) dy} \ .$$

The formula for the Mass of the Dark Matter particles

Energy Density: $\rho_{DM}(t) = g \int \frac{d^3P_f}{(2\pi)^3} \sqrt{m^2 + P_f^2}\ f_d[a(t)\, P_f]$

g : # of internal degrees of freedom of the DM particle,
$1 \leq g \leq 4$. For $z \lesssim 30 \;\Rightarrow$ DM particles are non-relativistic:

$\rho_{DM}(t) = m\ g\ \frac{T_d^3}{a^3(t)} \int_0^\infty y^2\ f_d(y)\ \frac{dy}{2\pi^2}$.

Using entropy conservation: $T_d = \left(\frac{2}{g_d}\right)^{\frac{1}{3}}\ T_\gamma\ (1 + z_d)$,

$g_d =$ effective # of UR degrees of freedom at decoupling,
$T_\gamma = 0.2348$ meV , $1\ \text{meV} = 10^{-3}$ eV.
Today $\Omega_{DM} = \rho_{DM}(0)/\rho_c = 0.105/h^2$ and we obtain for the mass of the DM particle:

$$m = 6.986\ \text{eV}\ \frac{g_d}{g \displaystyle\int_0^\infty y^2\ f_d(y)\ dy}$$

. Goal: determine m and g_d

Dark Matter density and DM velocity dispersion

Energy Density: $\rho_{DM}(t) = g \int \frac{d^3 P_f}{(2\pi)^3} \sqrt{m^2 + P_f^2}\; F_d[a(t)\, P_f]$

g : # of internal degrees of freedom of the DM particle, $1 \leq g \leq 4$. For $z \lesssim 30 \;\Rightarrow$ DM particles are non-relativistic:

$$\rho_{DM}(t) = \frac{m\, g}{2\pi^2}\, \frac{T_d^3}{a^3(t)} \int_0^\infty y^2\, F_d(y)\, dy\ ,$$

Using entropy conservation: $T_d = \left(\frac{2}{g_d}\right)^{\frac{1}{3}}\, T_{CMB}$,

$g_d =$ effective # of UR degrees of freedom at decoupling, $T_{CMB} = 0.2348\; 10^{-3}$ eV, and

$$\rho_{DM}(\text{today}) = \frac{m\, g}{\pi^2\, g_d}\, T_{CMB}^3 \int_0^\infty y^2\, F_d(y)\, dy = 1.107\, \frac{\text{keV}}{\text{cm}^3} \quad (1)$$

We obtain for the primordial velocity dispersion:

$$\sigma_{DM}(z) = \sqrt{\frac{1}{3}\, \langle \vec{V}^2 \rangle(z)} = 0.05124\, \frac{1+z}{g_d^{\frac{1}{3}}} \left[\frac{\int_0^\infty y^4\, F_d(y)\, dy}{\int_0^\infty y^2\, F_d(y)\, dy}\right]^{\frac{1}{2}} \frac{\text{keV}}{m}\, \frac{\text{km}}{\text{s}}$$

Goal: determine m and g_d. We need TWO constraints.

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

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

The phase-space density today follows observing dwarf spheroidal satellite galaxies of the Milky Way (dSphs)

$\frac{\rho_s}{\sigma_s^3} \sim 5 \times 10^3 \, \frac{\mathrm{keV/cm^3}}{(\mathrm{km/s})^3} = (0.18 \, \mathrm{keV})^4$ Gilmore et al. 07 and 08.

During structure formation $(z \lesssim 30)$, $Q = \rho/\sigma^3$ decreases by a factor that we call Z:

$$Q_{today} = \frac{1}{Z} \, Q_{prim} \quad , \quad Q_{prim} = \frac{\rho_{prim}}{\sigma_{prim}^3} \quad , \quad \text{(2)} \quad Z > 1.$$

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

Constraints: First $\rho_{DM}(\text{today})$, Second $Q_{today} = \rho_s/\sigma_s^3$

Phase-space density invariant under universe expansion

Using again entropy conservation to replace T_d yields for the one-dimensional velocity dispersion,

$$\sigma_{DM}(z) = \sqrt{\frac{1}{3}\,\langle\vec{V}^2\rangle(z)} = \frac{2^{\frac{1}{3}}}{\sqrt{3}}\,\frac{1+z}{g_d^{\frac{1}{3}}}\,\frac{T_\gamma}{m}\,\sqrt{\frac{\int_0^\infty y^4\,F_d(y)\,dy}{\int_0^\infty y^2\,F_d(y)\,dy}} =$$

$$= 0.05124\,\frac{1+z}{g_d^{\frac{1}{3}}}\,\frac{\mathrm{keV}}{m}\,\left[\frac{\int_0^\infty y^4\,F_d(y)\,dy}{\int_0^\infty y^2\,F_d(y)\,dy}\right]^{\frac{1}{2}}\,\frac{\mathrm{km}}{\mathrm{s}}.$$

Phase-space density: $\mathcal{D} \equiv \frac{n(t)}{\langle\vec{P}^2_{phys}(t)\rangle^{\frac{3}{2}}} \overset{\mathrm{non-rel}}{=} \frac{\rho_{DM}}{3\sqrt{3}\,m^4\,\sigma^3_{DM}}$

$\mathcal{D}$ is computed theoretically from freezed-out distributions:

$$\mathcal{D} = \frac{g}{2\,\pi^2}\,\frac{\left[\int_0^\infty y^2 F_d(y)dy\right]^{\frac{5}{2}}}{\left[\int_0^\infty y^4 F_d(y)dy\right]^{\frac{3}{2}}}$$

Theorem: The phase-space density $\mathcal{D}$ can only decrease under self-gravity interactions (gravitational clustering) [Lynden-Bell, Tremaine, Henon, 1986].

The Phase-space density ρ/σ^3 and its decrease factor Z

The phase-space density $\frac{\rho}{\sigma^3}$ is invariant under the cosmological expansion and can only decrease under self-gravity interactions (gravitational clustering).

The phase-space density today follows observing dwarf spheroidal satellite galaxies in the Milky Way (dSphs)

$\frac{\rho_s}{\sigma_s^3} \sim 5 \times 10^3 \; \frac{\mathrm{keV/cm^3}}{(\mathrm{km/s})^3} = (0.18 \; \mathrm{keV})^4$ Gilmore et al. 07 and 08.

During structure formation $(z \lesssim 30)$, ρ/σ^3 decreases by a factor that we call Z.

$$\frac{\rho_s}{\sigma_s^3} = \frac{1}{Z} \, \frac{\rho_{DM}}{\sigma_{DM}^3} \qquad (2)$$

N-body simulations results: $1000 > Z > 1$.

Constraints: First $\rho_{DM}(\mathrm{today})$, Second $\rho/\sigma^3(\mathrm{today}) = \rho_s/\sigma_s^3$

Mass Estimates for DM particles

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

$$m = \frac{2^{\frac{1}{4}} \sqrt{\pi}}{3^{\frac{3}{8}} \; g^{\frac{1}{4}}} \; Q_{prim}^{\frac{1}{4}} \; I_4^{\frac{3}{8}} \; I_2^{-\frac{5}{8}} \; , \quad g_d = \frac{2^{\frac{1}{4}} \; g^{\frac{3}{4}}}{3^{\frac{3}{8}} \; \pi^{\frac{3}{2}} \; \Omega_{DM}} \; \frac{T_\gamma^3}{\rho_c} \; Q_{prim}^{\frac{1}{4}} \; [I_2 \; I_4]^{\frac{3}{8}}$$

where: $Q_{prim}^{\frac{1}{4}} = Z^{\frac{1}{4}} \; 0.18$ keV using the dSphs data,

$T_\gamma = 0.2348 \text{ meV} \; , \; \Omega_{DM} = 0.228 \; , \; \rho_c = (2.518 \text{ meV})^4$

$I_{2n} = \int_0^\infty y^{2n} \; F_d(y) \; dy \quad , \quad n = 1, 2.$

These formulas yield for relics decoupling UR at LTE:

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

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

$1 < Z^{\frac{1}{4}} < 10$ for $1 < Z < 10000$. Example: for DM Majorana fermions $(g = 2)$ $m \simeq 0.85$ keV.

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:

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

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.

Mass Estimates of DM particles

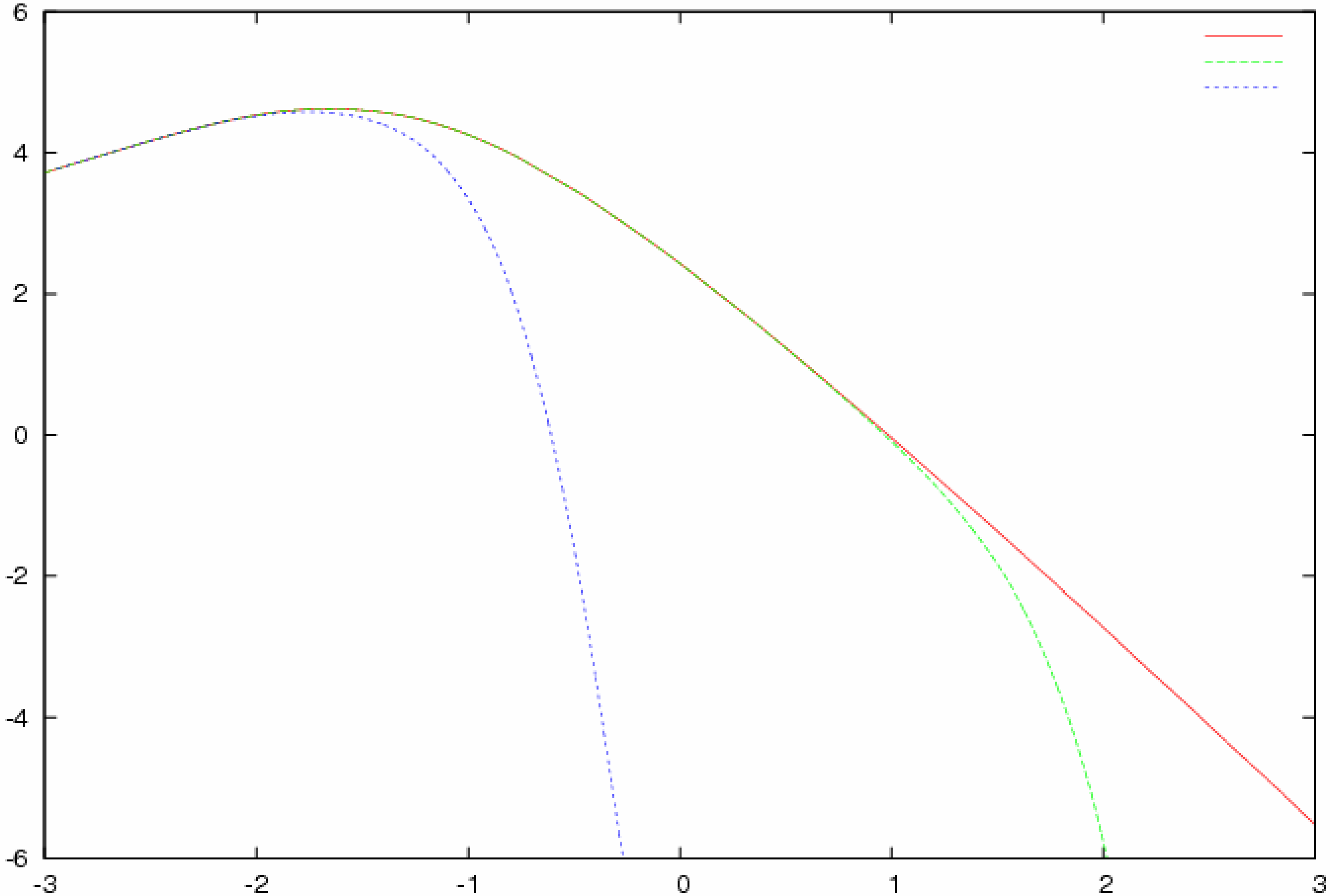
Our previous formulas yield for relics decoupling UR at LTE:

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

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.

Sterile neutrinos ν as DM decoupling out of LTE and UR.
ν is a singlet Majorana fermion with a Majorana mass m_ν coupled with a Yukawa-type coupling $Y \sim 10^{-8}$ to a real scalar field χ. χ is more strongly coupled to the particles in the Standard Model. [Chikashige,Mohapatra,Peccei (1981), Gelmini,Roncadelli (1981), Schechter, Valle (1982), Shaposhnikov, Tkachev (2006), Boyanovsky (2008)]

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 for scales < 100 kpc.

Transfer function in the MD era from Gilbert integral eq.

Relics decoupling non-relativistic

$$F_d^{NR}(p_c) = \frac{2^{\frac{5}{2}}\,\pi^{\frac{7}{2}}}{45}\; g_d\, Y_\infty\; \left(\frac{T_d}{m}\right)^{\frac{3}{2}}\; e^{-\frac{p_c^2}{2\,m\,T_d}} = \frac{2^{\frac{5}{2}}\,\pi^{\frac{7}{2}}}{45}\; \frac{g_d\, Y_\infty}{x^{\frac{3}{2}}}\; e^{-\frac{y^2}{2\,x}}$$

$Y(t) = n(t)/s(t)$, $n(t)$ number of DM particles per unit volume, $s(t)$ entropy per unit volume, $x \equiv m/T_d$, $T_d < m$.

$Y_\infty = \frac{1}{\pi}\sqrt{\frac{45}{8}}\;\frac{1}{\sqrt{g_d}\;T_d\;\sigma_0\;M_{Pl}}$ late time limit of Boltzmann.

σ_0: thermally averaged total annihilation cross-section times the velocity.

From our general equations for m and g_d:

$m = \frac{45}{4\,\pi^2}\;\frac{\Omega_{DM}\;\rho_c}{g\;T_\gamma^3\;Y_\infty} = \frac{0.748}{g\;Y_\infty}$ eV and $m^{\frac{5}{2}}\;T_d^{\frac{3}{2}} = \frac{45}{2\,\pi^2}\;\frac{1}{g\;g_d\;Y_\infty}\;Z\;\frac{\rho_s}{\sigma_s^3}$

Finally:

$$\sqrt{m\,T_d} = 1.47\;\left(\frac{Z}{g_d}\right)^{\frac{1}{3}}\,\mathrm{keV}. \quad m = 3.67\;\mathrm{keV}\;Z^{\frac{1}{3}}\;\frac{g_d^{\frac{1}{12}}}{\sqrt{g}}\;\sqrt{\frac{\sigma_0}{\mathrm{pb}}}$$

We used ρ_{DM} today and the decrease of the phase space density by a factor Z. 1 pb $= 10^{-36}\;\mathrm{cm}^2 = 0.257\;/(10^5\;\mathrm{GeV}^2)$.

Relics decoupling non-relativistic 2

Allowed ranges for m and T_d.

$m > T_d > b$ eV where $b > 1$ or $b \gg 1$ for DM decoupling in the RD era

$$\left(\frac{Z}{g_d}\right)^{\frac{1}{3}} 1.47 \text{ keV} < m < \frac{2.16}{b} \text{ MeV} \left(\frac{Z}{g_d}\right)^{\frac{2}{3}}$$

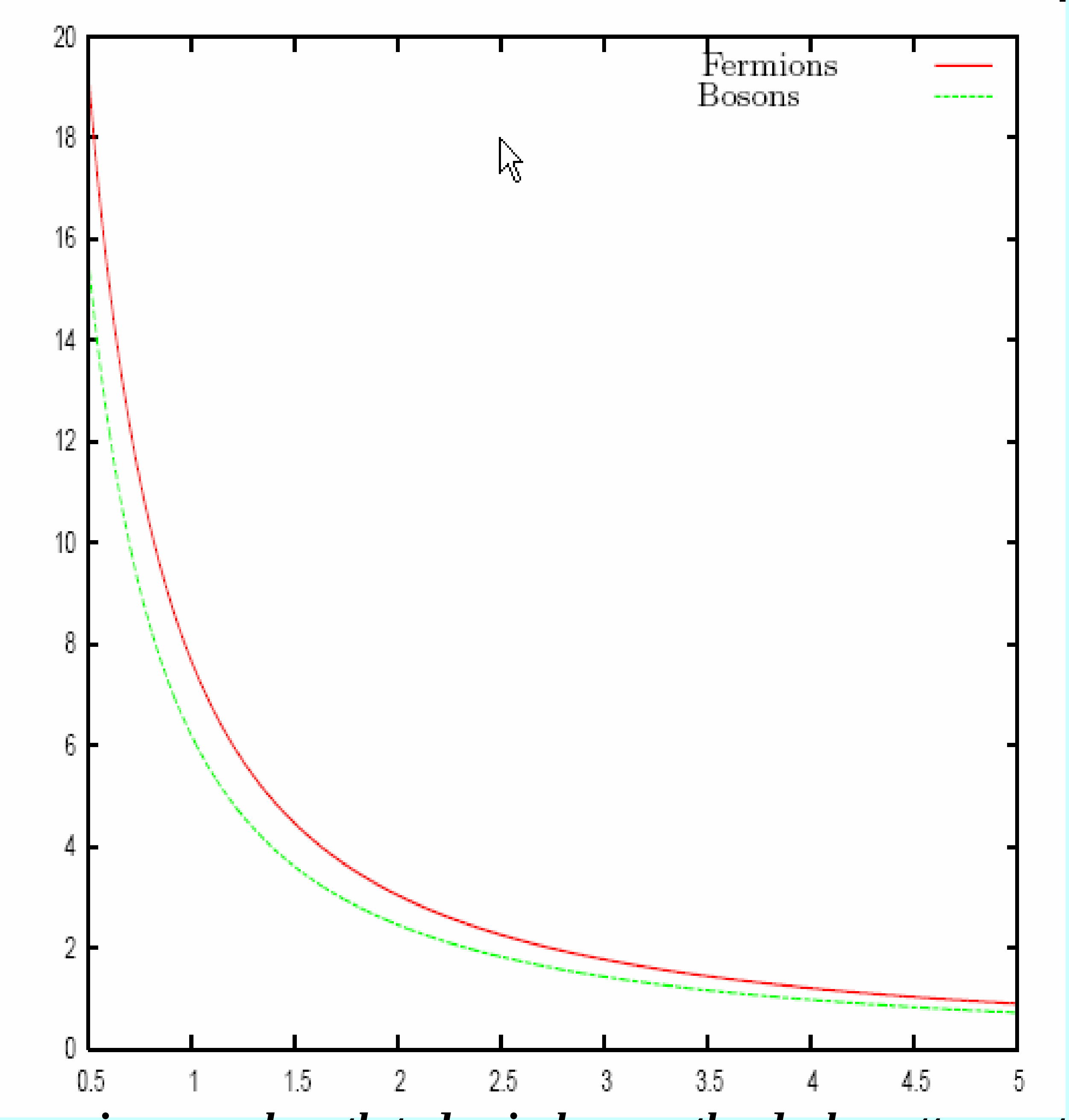
$g_d \simeq 3 \quad \text{for} \quad 1 \text{ eV} < T_d < 100 \text{ keV}$ and $1 < Z < 10^3$

$1.02 \text{ keV} < m < \frac{104}{b} \text{ MeV} \quad , \quad T_d < 10.2$ keV.

D. Boyanovsky, H. J. de Vega, N. Sanchez,
Phys. Rev. D 77, 043518 (2008), arXiv:0710.5180.
H. J. de Vega, N. G. Sanchez, arXiv:0901.0922.

Only using ρ_{DM} today (ignoring the phase space density information) gives:

$$\sigma_0 = 0.16 \text{ pbarn} \frac{g}{\sqrt{g_d}} \frac{m}{T_d}$$ http://pdg.lbl.gov



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 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

$$\mathbf{0.76\ kpc / (\sqrt{1+z}) < \lambda_{fs}(z) < 16.3\ kpc\ (\sqrt{1+z})}$$

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

These values at z = 0 are consistent with the N-body simulations and are of the order of the small dark matter structures observed today .

By the beginning of the matter dominated era $z \sim 3200$, the masses are of the order of galactic masses 10^{12} Msun and the comoving free-streaming length is of the order of the galaxy sizes today ~ 100 kpc

- **The self-gravity reduction factor Z of the phase space density D(z) is in the range 1 < Z < 10 000** for dwarf spheroidal galaxies dSphs. More accurate analysis of N body simulations should narrow this range which depends on the type and size of the galaxy considered.

Sharp decrease of the phase-space density with the redshift. This sharp decreasing is in agreement with the simulations in the violent merger phases followed by quiescent phases.

- The **mass of the dark matter particle,** independent of the particle model, **is in the keV scale** and the temperature when the dark matter particles decoupled is in the 100 GeV scale at least.

No assumption about the nature of the dark matter particle.
keV DM mass much larger than temperature in matter dominated era (which is less than 1 eV), the keV dark matter is cold (CDM).
m and Td are mildly affected by the uncertainty in the factor Z through a power factor 1/4 of this uncertainty, namely, by a factor $10^{1/4} \sim 1.8$.

- Lower and upper bounds for the dark matter annihilation cross-section σ_0 are derived:

$\sigma_0 > (0.239 - 0.956)\ 10^{-9}\ GeV^{-2}$ and $\sigma_0 < 3200\ m\ GeV^{-3}$.

There is at least five orders of magnitude between them , the dark matter non-gravitational self-interaction is therefore negligible (consistent with structure formation and observations, as well as by comparing X-ray, optical and lensing observations of the merging of galaxy clusters with N-body simulations).

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

In all cases: DM particles decoupling either ultra-relativistic or non-relativistic, LTE or OTE :

(i) the mass of the dark matter particle is in the keV scale, T_d is 100 GeV at least.

(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 negligable.

(iv) The keV scale mass dark matter determines cored (non cusped) dark matter halos.

(v) DM candidates with typical high masses 100 GeV, so called ("wimps") result strongly

CONSTRAINTS: SUMMARY

- ARBITRARY DECOUPLED DISTRIBUTION FUNCTION
- ABUNDANCE $\longrightarrow$ UPPER BOUND
- dSphs (DM dominated) PHASE SPACE

  $\longrightarrow$ LOWER BOUND
- m ~ keV THERMAL RELICS decoupled when relativistic 100-300 GeV consistent with CORES
- Wimps with m ~ 100 GeV, T_d ~ 10 MeV PSD ~ 10^{18}-10^{15} x (dSphs)

Transfer function and power spectrum:

- ❑ NR Boltzmann-Vlasov eqn for (DM) density + gravitational perturba
- ❑Valid for particles that are NR and modes inside Hubble radiu
- ❑ Matter domination $z \leq z_{eq} \sim 3050$
- ❑All scales relevant for structure formation

What's out?

❖ Photons + Baryons modify T(k) ~ few %

❖BAO on scales ~ 150 Mpc (acoustic horizon)
(interested in MUCH smaller scales)

Why?

✓ Study arbitrary distribution functions, couplings, masses

✓Analytical understanding of small scale properties

✓No tinkering with codes

$$f(\vec{p};\vec{x};t) = f_0(p) + F_1(\vec{p};\vec{x};t) \qquad \varphi(\vec{x},t) = \varphi_0(\vec{x},t) + \varphi_1$$

Unperturbed decoupled distribution

(DM) perturbation

Unperturbed grav. Potential (FRW)

Grav. Potential perturbation

Linearized B-V Equation:

$$\frac{1}{a}\frac{\partial F_1}{\partial \tau} + \frac{\vec{p}}{ma^2}\cdot\vec{\nabla}_{\vec{x}}F_1 - m\vec{\nabla}_{\vec{x}}\varphi_1\cdot\vec{\nabla}_{\vec{p}}f_0 = 0$$

Poisson Eqn: $\varphi_1(\vec{k};s) = -\dfrac{4\pi G}{k^2 a(s)}\Delta(\vec{k};s)$ $\quad \Delta(\vec{k},s) = m\displaystyle\int\frac{d^3p}{(2\pi)^3}F_1(\vec{k},\vec{p};s)$

``New'' variable s = $\dfrac{2u}{H_0\sqrt{\Omega_{DM}a_{eq}}}$; $\quad u = 1 - \left(\dfrac{a_{eq}}{a}\right)^{\frac{1}{2}} \longrightarrow \dfrac{ds}{d\tau} = \dfrac{1}{a}$

Follow the steps…

- Integrate B-V equation (in s)
- Use Poisson's eqn. ⟶ Integral eqn: Gilbert's

- Normalize at initial time (t_{eq}):

$$\Phi(\vec{k},u) = \frac{\varphi_1(\vec{k},u)}{\varphi_1(\vec{k},0)} \qquad \delta(k,u) = \frac{\Delta(k;u)}{\Delta(k;0)}$$

$$P_f(k) = T^2(k) P_i(k)$$

$$T(k) = \frac{5}{3}\Phi(k;1)$$

- Normalize the decoupled
- distribution function:

$$\tilde{f}_0(y) = \frac{f_0(y)}{\int_0^\infty y^2 f_0(y)dy}$$

comoving momentum

$$y = \frac{p}{T_{0,d}}$$

decoupling temp.

- Take 2 derivatives w.r.t. u: ⟶

$$\underbrace{\ddot{\delta}(k,u) - \frac{6\,\delta(k,u)}{(1-u)^2} + 3\gamma^2\,\delta(k,u)} - \underbrace{\int_0^u du'\,K(u-u')\,\frac{\delta(k,u')}{(1-u')^2}} = \underbrace{S_0(k;u)}$$

Jeans' Fluid equation: replace C^2_s by $<V^2>$

Correction to fluid description: memory of gravitational clustering

Free streaming solution in absence of gravity: INITIAL CONDITIONS

$$\gamma^2 = \frac{2k^2}{k_{fs}^2(t_{eq})}; \quad \underbrace{k_{fs}(t_{eq}) = \frac{0.0102}{\sqrt{\overline{y^2}}}\left[\frac{g_d}{2}\right]^{\frac{1}{3}} \frac{m}{\mathrm{keV}}[\mathrm{kpc}]^{-1}}; \quad \overline{y^2} = \int_0^\infty dy\, y^4\, \tilde{f}_0(y)$$

Free streaming wave vector at matter-radiation equality

$$k_{fs}(t_{eq}) = \begin{cases} \dfrac{5.88}{\mathrm{pc}}\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\left(\dfrac{m}{100\,\mathrm{GeV}}\right)^{\frac{1}{2}}\left(\dfrac{T_d}{10\,\mathrm{MeV}}\right)^{\frac{1}{2}} & \text{WIMPs} \\ 0.00284\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\dfrac{m}{\mathrm{keV}}[\mathrm{kpc}]^{-1} & \text{FD thermal relics} \\ 0.00317\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\dfrac{m}{\mathrm{keV}}[\mathrm{kpc}]^{-1} & \text{BE thermal relics} \end{cases}$$

$$K(u-u') = 6\alpha \int_0^\infty y\,(\overline{y^2} - y^2)\; \tilde{f}_0(y) \sin[\alpha\, \dot{y}\,(u-u')]\, dy \qquad \alpha = \sqrt{\frac{3}{\overline{y^2}}}\,\gamma$$

DECOUPLED DISTRIBUTION FUNCTION: **STATISTICS**

Properties of K(u-u'):

- Correction to fluid description
- Memory of gravitational clustering $\longrightarrow$
- $f_0(y)$ with larger support for small y $\longrightarrow$
- **longer range of memory**
- Longer range of memory → → → **larger T(k)**
- Negligible at **large** scales $k << k_{fs}(t_{eq})$
- Important at **small** scales $k \geq k_{fs}(t_{eq})$

Exact T(k)

$$T(k) = \frac{10}{\sqrt{3}\,\gamma^3}\int_0^1 h_2(u)\Big[\frac{I[\alpha u]}{(1-u)^2} + \frac{1}{6} S_{NB}[\delta;u]\Big]du$$

Regular solution of Jeans' Fluid eqn.

Free streaming solution In absence of gravity: INITIAL CONDITIONS

Memory of gravitational clustering: K(u-u')

Features:

- ✓ **Systematic Fredholm expansion**
- ✓ **First TWO terms simple and remarkably accurate**
- ✓ **Include memory of gravitational clustering**
- ✓ **Arbitrary distribution function(statistics+non LTE)**
- ✓ **Arbitrary initial conditions**

Summary: Roadmap

(1) ***Microphysics:*** **Particle physics model independent, kinetics, decoupling** $\longrightarrow f(y)$ **= decoupled distribution function, $y = p/T_{0,d}$**

(2) ***Constrain*** **mass, couplings, $T_{0,d}$ from abundance + phase space density**

$$\underbrace{\frac{100\,\mathrm{eV}}{D^{\frac{1}{4}}}}_{} \leq m \leq 6.5\,\mathrm{eV}\,\frac{g_d}{\underbrace{g\int_0^\infty y^2\, f(y)\,dy}_{}}\;; \qquad D = \frac{g}{2\pi^2}\,\frac{\left[\int_0^\infty y^2 f(y)dy\right]^{\frac{5}{2}}}{\left[\int_0^\infty y^4 f(y)dy\right]^{\frac{3}{2}}}$$

Lower bound from phase Space density of dSphs

Upper bound from abundance

Thermal relics that decouple relativistically: $D \sim 2\times10^{-3} \longrightarrow$ m ~ keV

(3) DM T(k): exact $\longrightarrow$ ***simple + accurate approx:***

arbitrary f(y)+ini. conds.

corrections to fluid+ memory of grav. clustering.

large f(y) at small y=long memory=large T(k) at small scales.

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.

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

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

Long distance tail reproduce galaxy rotation curves.

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, $\rho_0 =$ 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

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 $0.001 \, \mathrm{pc} < r_0 < 100$ pc (Larson laws, 1981).

DM surface density from linear Boltzmann-Vlasov eq

The distribution function of the decoupled DM particles:

$$f(\vec{x}, \vec{p}; t) = g\ f_0(p) + F_1(\vec{x}, \vec{p}; t)$$

$f_0(p) =$ thermal equilibrium function at temperature T_d.

We evolve the distribution function $F_1(\vec{x}, \vec{p}; t)$ according to the linearized Boltzmann-Vlasov equation since the end of inflation where the primordial inflationary fluctuations are:

$$|\phi_k| = \sqrt{2}\ \pi\ \frac{|\Delta_0|}{k^{\frac{3}{2}}}\ \left(\frac{k}{k_0}\right)^{\frac{n_s-1}{2}}$$ where

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

We Fourier transform over $\vec{x}$ and integrate over momentum

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

The matter density fluctuations $\rho_{lin}(r)$ are given today by

$$\rho_{lin}(r) = \frac{1}{2\,\pi^2\,r}\ \int_0^\infty k\ dk\ \sin(k\,r)\ \Delta(k, t_{\mathrm{today}})$$

The Gilbert equation

Define: $\widehat{\Delta}(k,t) \equiv \Delta(k,t)/\Delta(k,t_{eq})$.

The Gilbert equation takes the form:

$$\widehat{\Delta}(k,u) - \frac{6}{\alpha}\int_0^u \Pi[\alpha\,(u-u')]\,\frac{\widehat{\Delta}(k,u')}{[1-u']^2}\,du' = I[\alpha\,u]$$

where,

$$\Pi[z] = \frac{1}{I_2}\int_0^\infty dy\;y\;f_0(y)\;\sin(y\,z),\;\; I[z] = \frac{1}{I_2}\int_0^\infty dy\;y\;f_0(y)\;\frac{\sin(y\,z)}{z}$$

$$y \equiv \frac{p}{T_d}, \quad z \equiv \alpha\,u, \quad \alpha \equiv \frac{2\,k}{H_0}\sqrt{\frac{1+z_{eq}}{\Omega_M}}\;\frac{T_d}{m},$$

$$I_2 = \int_0^\infty dy\;y^2\;f_0(y), \quad 1+z_{eq} = \frac{1}{a_{eq}} \simeq 3200,$$

$u =$ dimensionless time variable,

$$u = 1 - \sqrt{\frac{a_{eq}}{a}}\;,\; 0 \le u \le u_{\text{today}} = 1 - \sqrt{a_{eq}} \simeq 0.982$$

$$a(u) = \frac{a_{eq}}{(1-u)^2}\;,\; a(\text{today}) = 1\;.$$

$$\widehat{\Delta}(k,t) \overset{t\to t_{\text{today}}}{=} \frac{3}{5}\,T(k)\,(1+z_{eq}), \quad T(k) = \text{transfer function.}$$

The solution of the Gilbert equation today

Transfer function: $T(0) = 1$ and $T(k \to \infty) = 0$.

The solution of the Gilbert equation $\widehat{\Delta}(k,t)$ for $k < k_{fs}$ grow proportional to the scale factor.

$k_{fs} =$ free-streaming (Jeans) comoving wavenumber.

$k_{fs} =$ characteristic scale for the decreasing of $T(k)$ with k

$\Longrightarrow$ the natural variable here is $\gamma \equiv k \, r_{lin}$

$r_{lin} \equiv \frac{\sqrt{2}}{k_{fs}} = \frac{2}{H_0} \, \sigma_{DM} \, \sqrt{\frac{1+z_{eq}}{\Omega_M}}$ and

$$\sigma_{DM} = \left(3 \;\, M_{Pl}^2 \, H_0^2 \, \Omega_{DM} \, \frac{1}{Z} \, \frac{\sigma_s^3}{\rho_s}\right)^{\frac{1}{3}} \Longrightarrow r_{lin} = 125.1 \;\, \left(\frac{10}{Z}\right)^{\frac{1}{3}} \text{ kpc}$$

Collecting all formulas we obtain for the fluctuations today

$$\Delta(k, t_{\text{today}}) = 1.926 \, \frac{M_{Pl}^2}{H_0} \, |\Delta_0| \, T(k) \;\, \left(\frac{k}{k_0}\right)^{n_s/2-2} \;\, \log\left(0.116 \, \frac{k}{k_{eq}}\right)$$

Linear density fluctuations today

$$\Delta(k,z) \stackrel{z\to 0}{=} \frac{3}{5}\, T(k)\, (1+z_{eq})\, \Delta(k,z_{eq}) \quad , \quad {}_{eq} = \text{equilibration},$$

$T(k) =$ transfer function during the matter dominated era

$T(0)=1 \quad , \quad T(k\to\infty)=0$ and $1+z_{eq} \simeq 3200$.

$T(k)$ decreases with k with the characteristic free streaming scale $k_{fs} = \sqrt{2}/r_{lin}$,

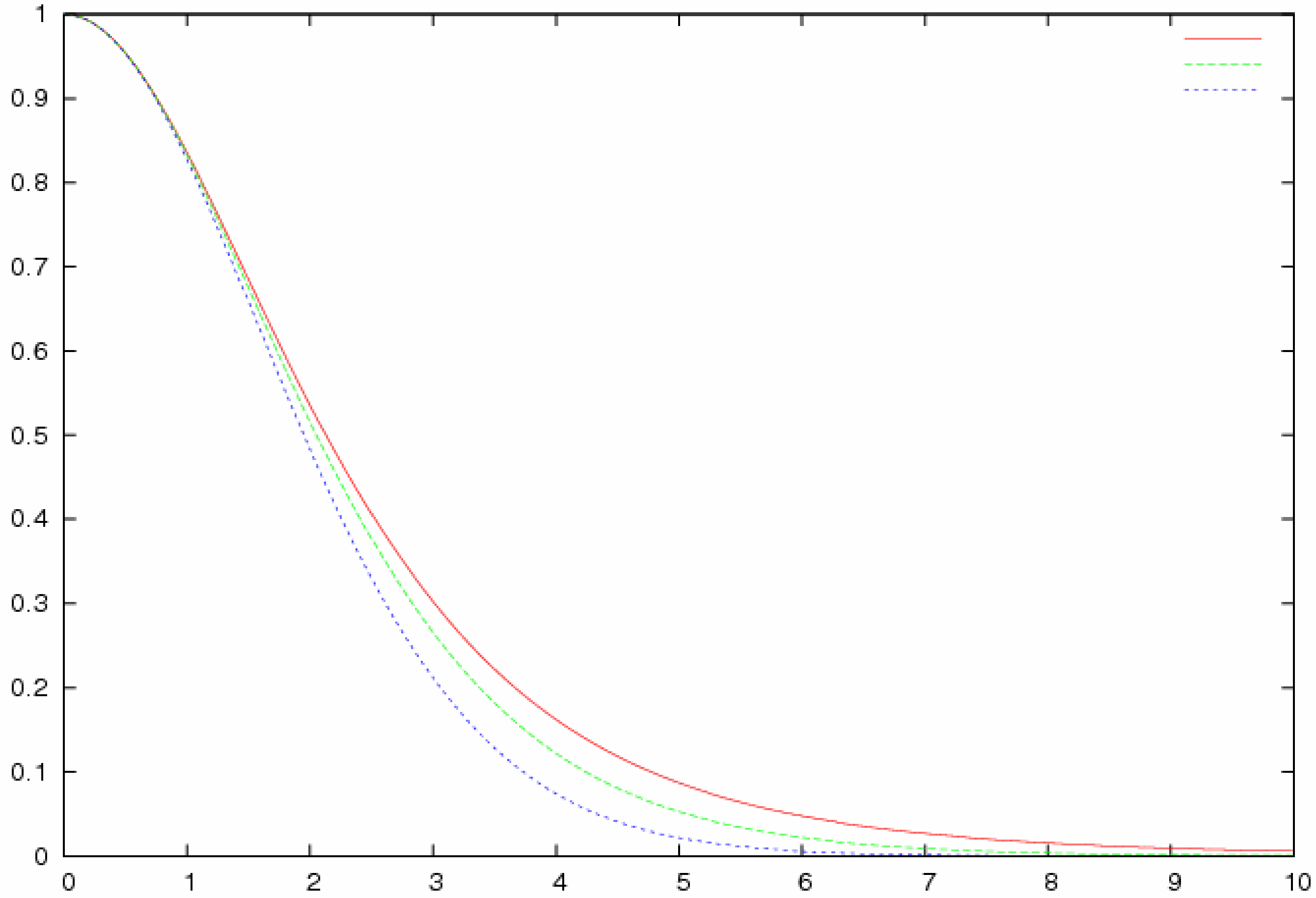
$$r_{lin} = 2\,\sqrt{1+z_{eq}}\,\left(\frac{3\,M_{Pl}^2}{H_0\,\sqrt{\Omega_{DM}}\,Q_{prim}}\right)^{\frac{1}{3}} \quad \text{and} \quad \gamma \equiv k\, r_{lin}.$$

The linear profile today results:

$$\rho_{lin}(r) = \frac{27\,\sqrt{2}}{5\,\pi}\,\frac{\Omega_M^2\,M_{Pl}^2\,H_0}{\sigma_{DM}^2}\,b_0\,b_1\,9.6\,|\Delta_0|\,\left(k_{eq}\,r_{lin}\right)^{\frac{3}{2}} \times$$
$$\left(k_0\,r_{lin}\right)^{\frac{1-n_s}{2}}\,\frac{1}{r}\,\int_0^\infty d\gamma\,N(\gamma)\,\sin\left(\gamma\,\frac{r}{r_{lin}}\right)$$

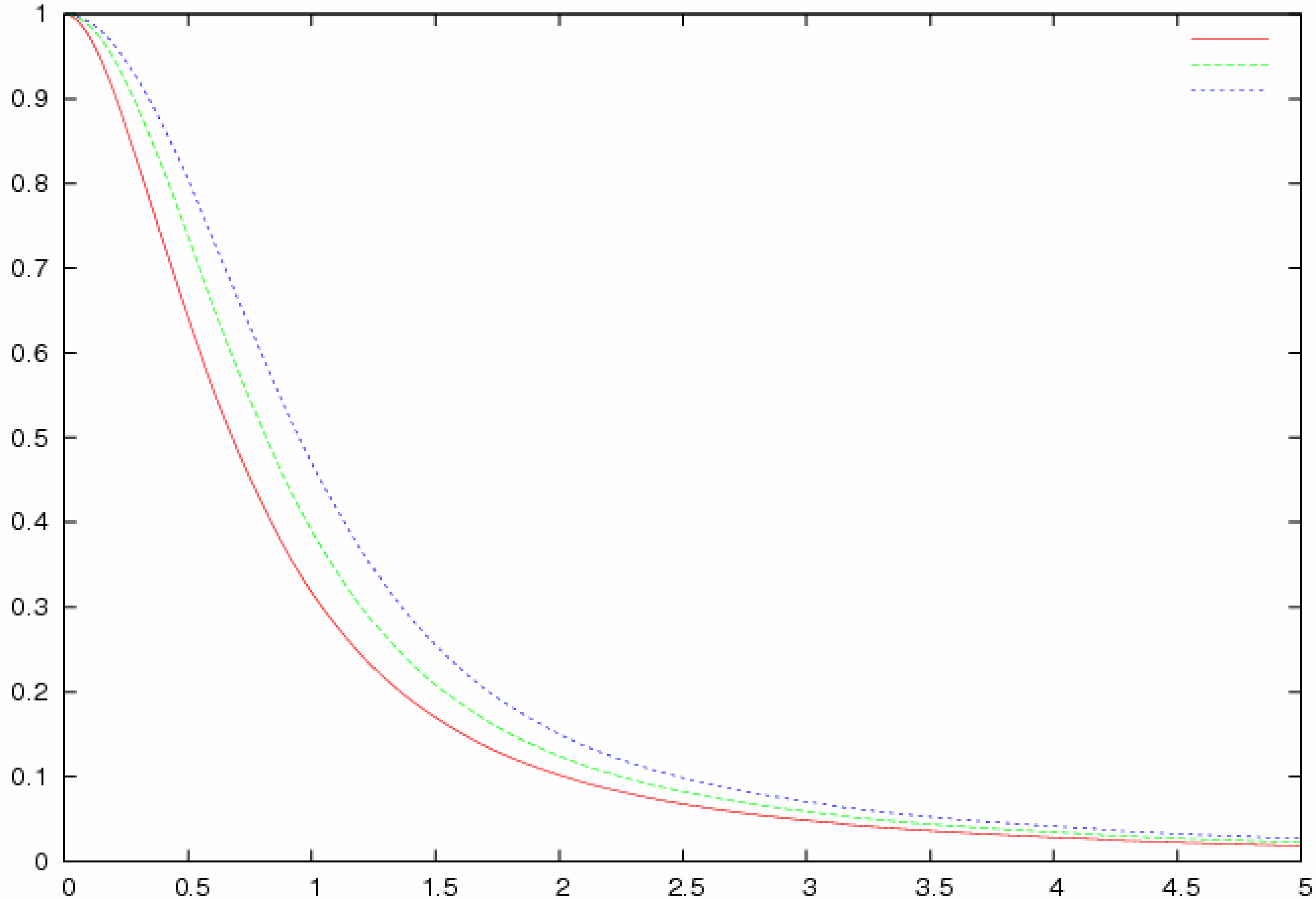
where $N(\gamma) \equiv \gamma^{n_s/2-1}\,\log\left(\frac{c\,\gamma}{k_{eq}\,r_{lin}}\right)\,T(\gamma) \quad , \quad c \simeq 0.11604.$

Transfer function $T(k)$



$T(k)$ vs. $\gamma = k\ r_{lin}$ for Fermions and Bosons decoupling ultrarelativistically and for particles decoupling non-relativistically (Maxwell-Boltzmann statistics).

Density profiles in the linear approximation



Profiles $\rho_{lin}(r)/\rho_{lin}(0)$ vs. $x \equiv r/r_{lin}$. These are universal profiles as functions of x. r_{lin} depends on the galaxy.

Fermions and Bosons decoupling ultrarelativistically and particles decoupling non-relativistically (Maxwell-Boltzmann statistics)

Matching the observed and the theoretical surface density

Surface density: $\mu_0 \equiv r_0 \, \rho(0)$ where $r_0 =$ core radius.

Linear approximation: $r_{lin} = \alpha \, r_0$. α follows fitting the linear profile $\rho_{lin}(r)$ to the Burkert profile with core radius r_0.

$\alpha-$values: $\alpha_{BE} = 0.805 \, , \alpha_{FD} = 0.688 \, , \alpha_{MB} = 0.421$.

Theoretical result: $\mu_{0\,lin} = r_{lin} \; \rho_{lin}(0)/\alpha$.

Fermions:

$$\mu_{0\,lin} = 8261 \; \left[\frac{Q_{prim}}{(\text{keV})^4}\right]^{0.161} \left[1 + 0.0489 \; \ln \frac{Q_{prim}}{(\text{keV})^4}\right] \text{MeV}^3$$

Here: $0.161 = n_s/6$

Matching the observed values $\mu_{0\,obs}$ with this $\mu_{0\,lin}$ gives $Q_{prim}/(\text{keV})^4$ and the mass of the DM particle as

$$m = m_0 \; Q_{prim}^{\frac{1}{4}}/\text{keV}$$

BE: $m_0 = 2.6462$ keV, FD: $m_0 = 2.6934$ keV.

The distribution function Today

We obtain solving the linearized Boltzmann-Vlasov since the end of inflation:

$$\rho_{lin}(r) = \rho_{lin}(0)\; F(r/r_{lin})$$

Characteristic scale for the density profile decrease:

$r_{lin} \equiv \frac{\sqrt{2}}{k_{fs}} = 58.1 \;\left(\frac{100}{Z}\right)^{\frac{1}{3}}$ kpc $\sim$ free streaming length.

Recall,

$m \simeq Z^{\frac{1}{4}}$ keV for UR decoupling

and $m \simeq Z^{\frac{1}{3}}$ keV for NR decoupling.

H. J. de Vega, N. G. Sanchez,
On the constant surface density in dark matter galaxies and interstellar molecular clouds, arXiv:0907.0006

Density profiles in the linear approximation

Particle Statistics	$\mu_{0D} = r_{lin}\, \rho_{lin}(0)$, $n_s/6 = 0.16$
Bose-Einstein	$(18.9 \text{ Mev})^3\ (Z/100)^{0.16}$
Fermi-Dirac	$(17.7 \text{ Mev})^3\ (Z/100)^{0.16}$
Maxwell-Boltzmann	$(16.7 \text{ Mev})^3\ (Z/100)^{0.16}$

Observed value: $\mu_{0D} \simeq (17.6 \text{ Mev})^3 \Rightarrow Z \sim 10 - 1000$

The linear profiles obtained are cored at the scale r_{lin}

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

$$\rho_{lin}(r) \overset{r \gg r_{lin}}{=} r^{-1-n_s/2} = r^{-1.482} \quad ,$$

in agreement 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.

Linear results for μ_{0D} and the profile vs. observations

Since the surface density $r_0 \, \rho(0)$ should be universal, we can identify $r_{lin} \, \rho_{lin}(0)$ from a spherically symmetric solution of the linearized Boltzmann-Vlasov equation.

The linear profiles obtained are cored since $T(k)$ decays for $k > k_{fs} \sim 1/r_{lin} \sim 0.008 \, (Z/10)^{\frac{1}{3}} \, (\text{kpc})^{-1}$.

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

$\rho_{lin}(r) \stackrel{r \gg r_{lin}}{=} r^{-1-n_s/2} = r^{-1.482}$,

in agreement with the universal empirical behaviour $r^{-1.6 \pm 0.4}$, M. G. Walker et al., (2009).

For larger scales nonlinear effects from small k should give the customary r^{-3} tail.

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

The comparison of our theoretical values for μ_{0D} and the observational value indicates that $Z \sim 10 - 100$.

This implies that the DM particle mass is in the keV range.

Non-universal galaxy properties.

	Observed Values	Linear Theory
r_0	5 to 52 kpc	46 to 59 kpc
ρ_0	1.57 to 19.3×10^{-25} $\frac{\text{g}}{\text{cm}^3}$	1.49 to 1.91×10^{-25} $\frac{\text{g}}{\text{cm}^3}$
$\sqrt{\overline{v^2}_{halo}}$	79.3 to 261 km/sec	260 km/sec

Dark matter particle mass: $1.6 < m < 2$ keV.

The larger and less denser are the galaxies, the better are the results from the linear theory for non-universal quantities.

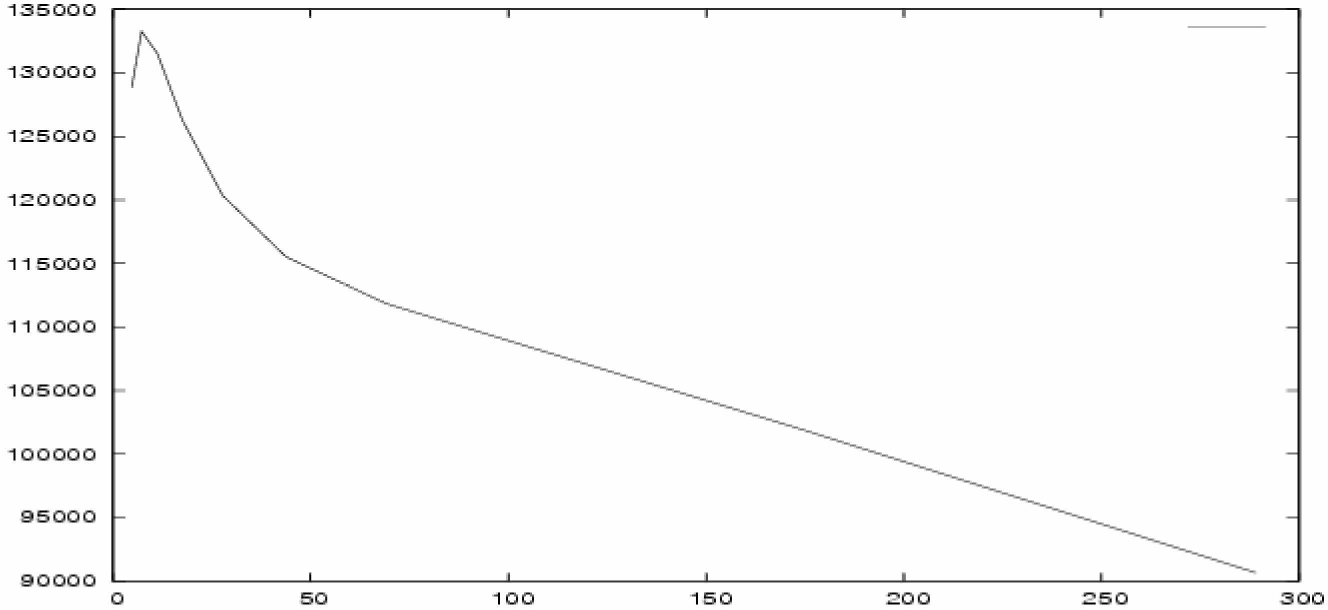
The linear approximation turns to improve for larger galaxies $r_0 > 70$ kpc (i. e. more diluted).

Therefore, universal quantities can be reproduced by the linear approximation.

Density Contrast

Ratio between the maximum DM mass density $\rho_{lin}(0)$ and the average DM mass density $\bar{\rho}_{DM}$ in the universe

$$\text{contrast} \equiv \frac{\rho_{lin}(0)}{\bar{\rho}_{DM}} = \frac{\mu_{0\,lin}}{\Omega_{DM}\ \rho_c\ r_0}$$



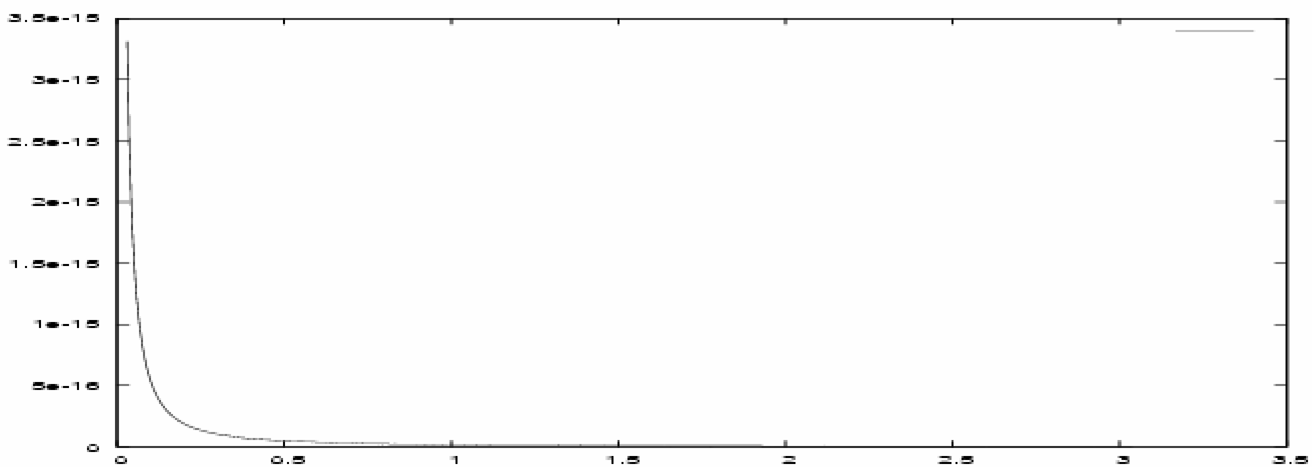
The linear contrast turns to be between 1/3 and 1/2 of the observed value $\sim 3 \times 10^5$ (Salucci & Persic, 1997).

Linear galaxies are less dense and larger than the observations. Universal quantities take the right values.

Wimps vs. galaxy observations

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

CONCLUSIONS

(I) THE MASS OF THE DARK MATTER PARTICLE

(II) THE BOLTZMAN VLASOV EQUATION:
TRANSFERT FUNCTION AND ANALYTIC RESULTS

(III) UNIVERSAL PROPERTIES OF GALAXIES:
DENSITY PROFILES, SURFACE DENSITY,
AND THE POWER OF LINEAR APPROXIMATION

Microphysics: Particle physics model, kinetics of production, decoupling

$\longrightarrow \quad f(y)$ = decoupled distribution function, $y=p/T_{0,d}$

Constrain mass, couplings, $T_{0,d}$ ***from abundance + phase space density***

$$\underbrace{\frac{100\,\mathrm{eV}}{\mathcal{D}^{\frac{1}{4}}}}_{\text{ound from phase ensity of dSphs}} \leq m \leq 6.5\,\mathrm{eV}\,\underbrace{\frac{g_d}{g\int_0^\infty y^2 f(y)\,dy}}_{\text{Upper bound from abundance}} \quad ; \quad \mathcal{D} = \frac{g}{2\pi^2}\frac{\left[\int_0^\infty y^2 f(y)dy\right]^{\frac{5}{2}}}{\left[\int_0^\infty y^4 f(y)dy\right]^{\frac{3}{2}}}$$

hermal relics that decouple
stically:

$$\mathcal{D} \sim \Lambda \times 10^{-2} \sim 10^{-4} \longrightarrow$$ m ~ keV

l T(k): exact $\longrightarrow$ ***simple + accurate approx:***

- ***arbitrary f(y)+ini. conds.***
- ***corrections to fluid+ memory of grav. clustering.***

Summary: keV scale DM particles

- Reproduce the phase-space density observed in dwarf satellite galaxies and spiral galaxies (dV S 2009).
- Provide cored universal galaxy profiles in agreement with observations (dV S 2009,dV S S 2010). (Review on cores vs. cusps by de Blok 2010).
- Reproduce the universal surface density μ_0 of DM dominated galaxies (dV S S 2010). WIMPS simulations give 10^9 times the observed value of μ_0 (Hoffman et al. 2007).
- Alleviate the satellite problem which appears when wimps are used (Avila-Reese et al. 2000, Götz & Sommer-Larsen 2002)
- Alleviate the voids problem which appears when wimps are used (Tikhonov et al. 2009).

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 explained by astrophysics: P.L. Biermann, et al. (2009), P. Blasi, P. D. Serpico, (2009).
- Peculiar velocities. Wimps simulations predict velocities below the observed values by factors $4 - 10$ (Kashlinsky et al. 2008, Watkins et al. 2009, Lee & Komatsu 2010). keV scale DM should alleviate this problem.
- Galaxies from Wimps simulations are too small (Ryan Joung et al. 2009, Holz & Perlmutter 2010). keV scale DM may alleviate this problem.

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

Future Perspectives

The Golden Age of Cosmology and Astrophysics continues.

A wealth of data from WMAP (7 yr), Planck, Atacama Cosmology Tel and further experiments are coming.

Galaxy and Star formation. DM properties from astronomical observations. Better bounds on DM cross-sections.

DM in planets and the earth. Flyby and Pioneer anomalies?

The Dark Ages...Reionisation...the 21cm line...

Nature of Dark Energy? 76% of the energy of the universe.

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

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

Sterile neutrinos? Some unknown light particle ??

Need to learn about the physics of light particles (< 1 MeV).

(I) 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)**

(II) 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)**

(III) DENSITY PROFILES, SURFACE DENSITY, DARK MATTER PARTICLE MASS

H. J. De Vega, N.G. Sanchez ***On the constant surface density in dark matter galaxies and interstellar molecular clouds*** **arXiv:0907.006**

H. J. De Vega, P. Salucci, N.G. Sanchez ***Universal galaxy properties and the mass of the dark matter particle from theory and observations: the power of the linear approximation*** **arXiv:1004.1908**

END

THANK YOU FOR YOUR ATTENTION