Galaxy and cosmological motivations to the search of warm dark matter sterile neutrinos

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Dark Matter in the Universe

81 % of the matter of the universe is DARK (DM).
DM is the dominant component of galaxies.

DM interacts through gravity.

Further DM interactions unobserved so far. Such couplings must be very weak: much weaker than weak interactions.

DM is outside the standard model of particle physics.

Proposed candidates:

- Neutrinos: HDM, (in the 1980's) $m \sim 1$ eV.
- Cold Dark Matter: CDM, WIMPS, $m \sim 10 - 1000$ GeV.
- Warm Dark Matter: WDM, sterile neutrinos $m \sim 1$ keV.

Dark Matter Particles

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

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

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

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

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

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

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

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

CDM free streaming scale

For CDM particles with $m \sim 100$ GeV $\Rightarrow \; r_{Jeans} \sim 0.1$ pc.

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

This is a robust result of N-body CDM simulations but never observed in the sky.

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

CDM has many serious conflicts with observations:

Galaxies naturally grow through merging in CDM models.

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

Pure-disk galaxies (bulgeless) are observed whose formation through CDM is unexplained.

CDM predicts cusped density profiles: $\rho(r) \sim 1/r$ for small r.

Observations show cored profiles: $\rho(r)$ bounded for small r.

Structure Formation in the Universe

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

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

Structures form through non-linear gravitational evolution.

Hierarchical formation starts from small scales first.

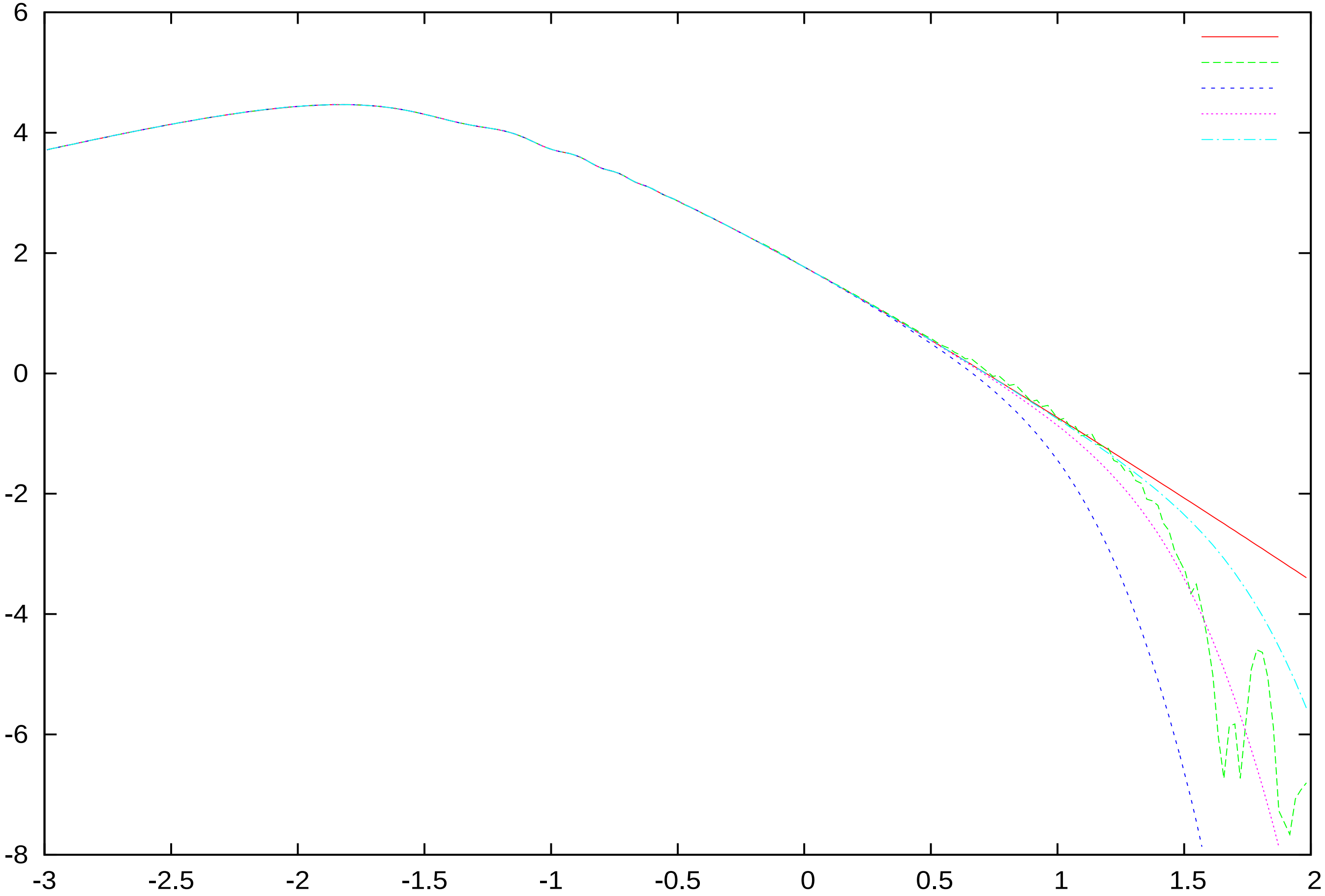
N-body CDM simulations fail to produce the observed structures for small scales less than some kpc.

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

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

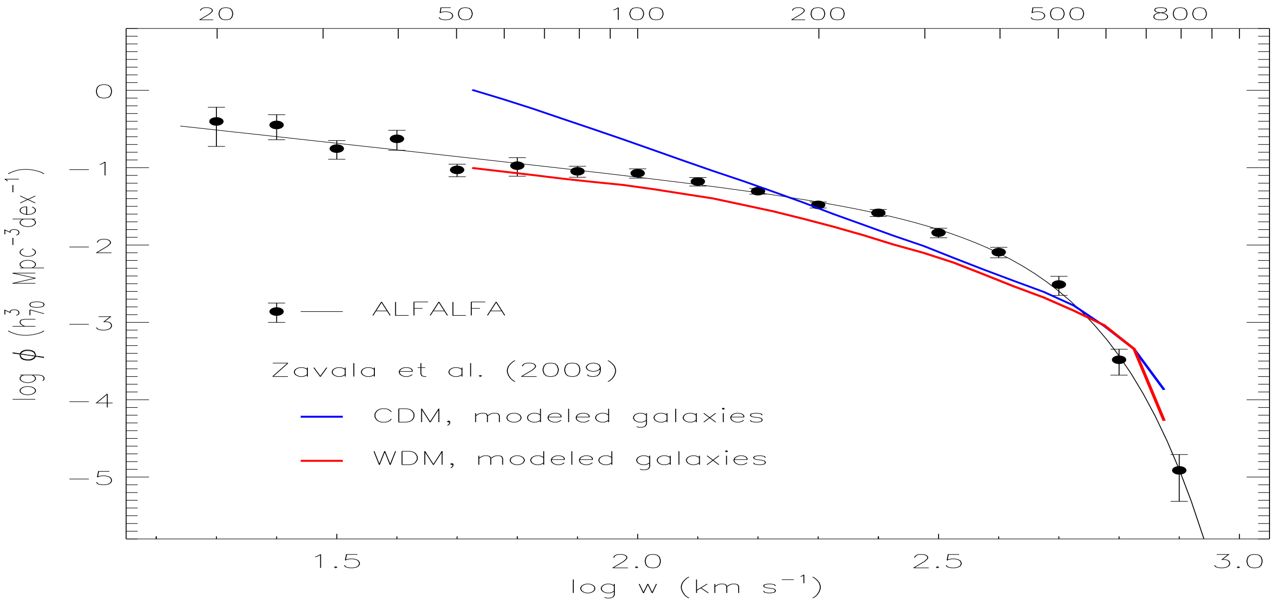
Primordial power $P(k)$: first ingredient in galaxy formation.

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



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

Velocity widths in galaxies: test substructure formation

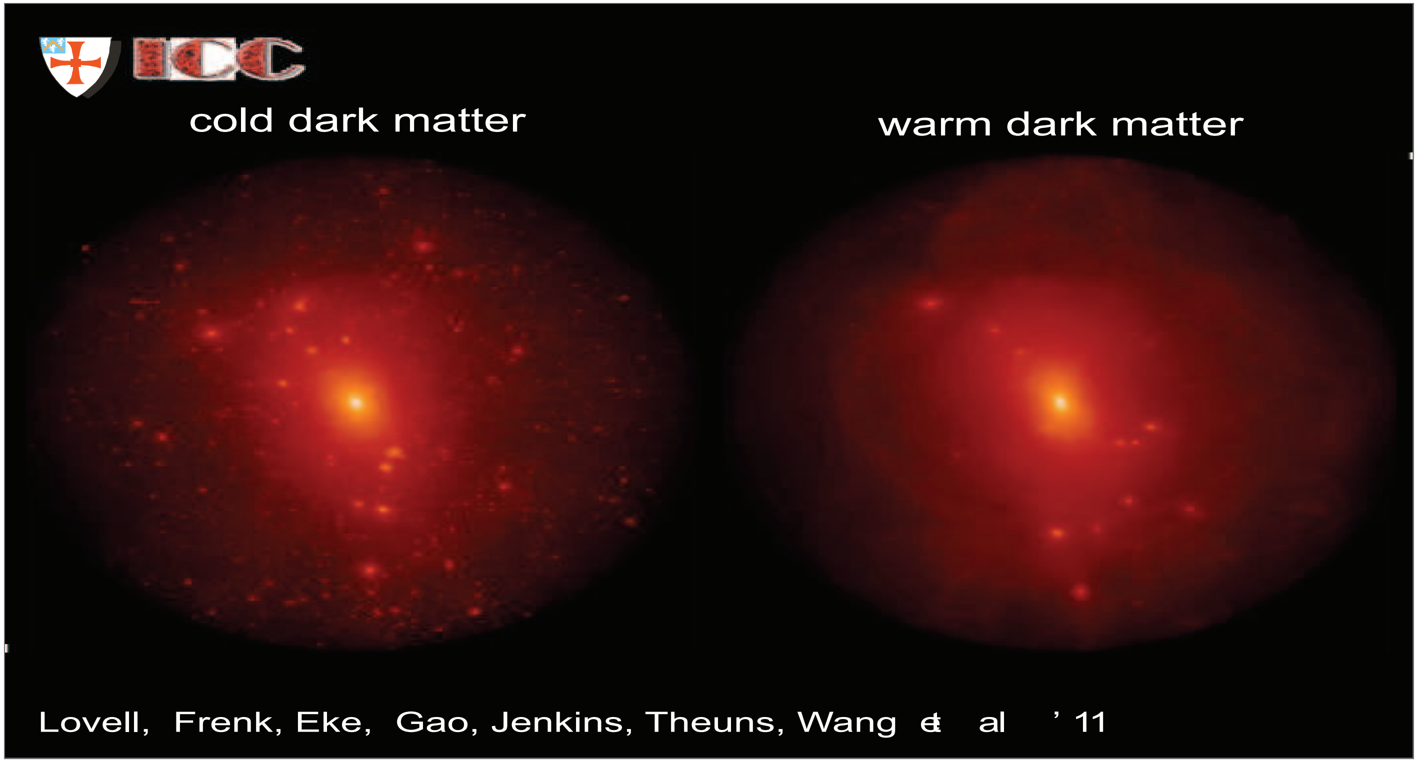


Velocity widths in galaxies from 21cm HI surveys. ALFALFA survey clearly favours WDM over CDM. (Papastergis et al. ApJ, 2011, Zavala et al. ApJ, 2009).

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.

N-body WDM Simulations: substructure formation



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. MNRAS (2012).

Summary: WDM produces correct substructure abundance.

Dwarf galaxies as quantum objects

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

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

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

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

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

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

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

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

Quantum pressure vs. gravitational pressure

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

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

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

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

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

Equilibrium: $P_q = P_G \Longrightarrow$

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

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

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

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

Self-gravitating Fermions in the Thomas-Fermi approach

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

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

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

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

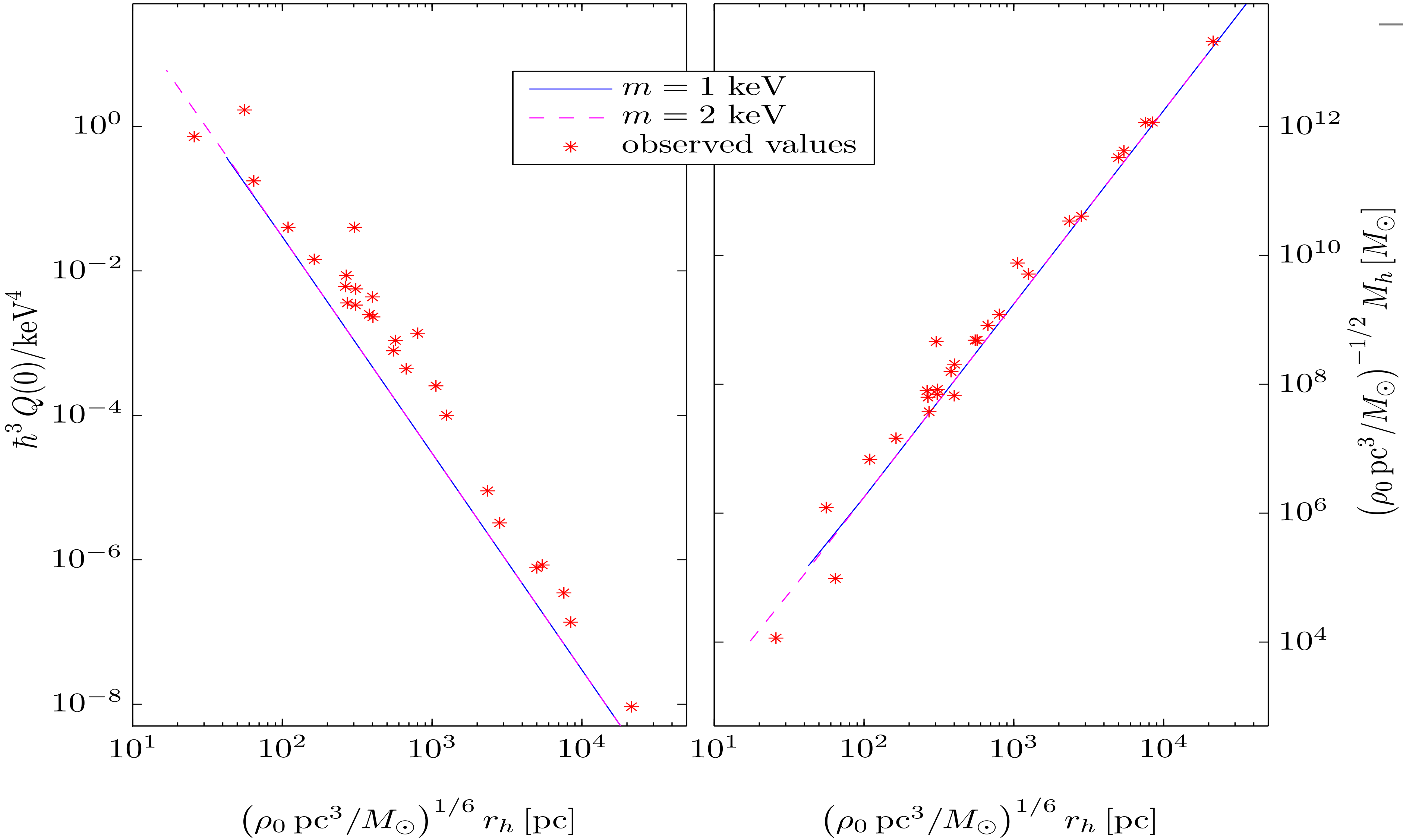
Density $\rho(r)$ and pressure $P(r)$ in terms of the distribution function $f(E)$:

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

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

Boundary condition at
$r = R = R_{200} \sim R_{vir}$, $\rho(R_{200}) \simeq 200\,\bar{\rho}_{DM}$

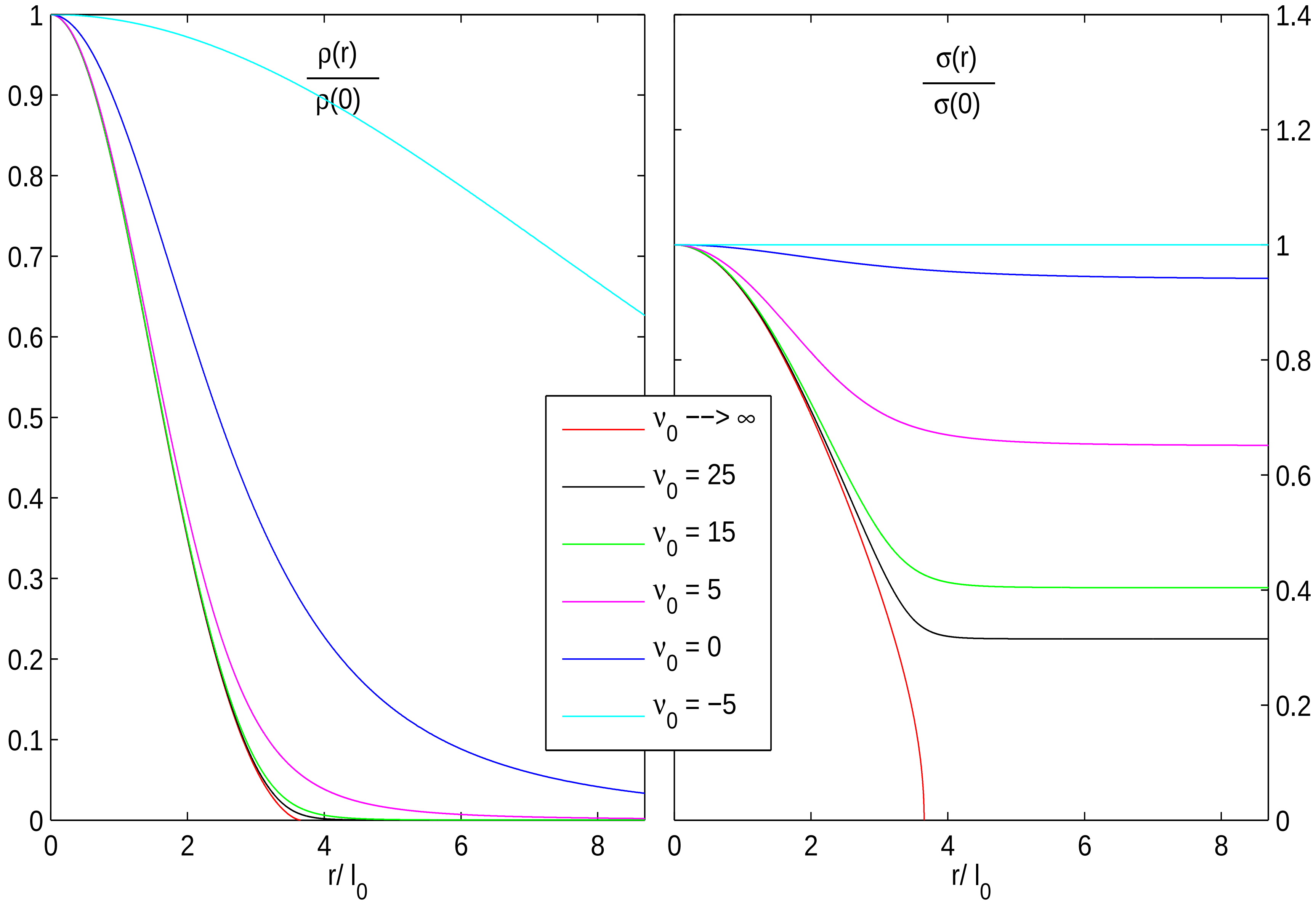
Q vs. halo radius. Galaxy observations vs. Thomas-Fermi



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

Density and velocity profiles from Thomas-Fermi

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



Self-gravitating Fermions in the Thomas-Fermi approach

The Thomas-Fermi approach gives physical galaxy magnitudes: mass, halo radius, phase-space density and velocity dispersion fully compatible with observations from the largest spiral galaxies till the ultracompact dwarf galaxies for a WDM particle mass around 2 keV.

Compact dwarf galaxies are close to a degenerate WDM Fermi gas while large galaxies are classical WDM Boltzmann gases.

Fermionic WDM treated quantum mechanically is able to reproduce the observed galaxies.

C. Destri, H. J. de Vega, N. G. Sanchez,
arXiv:1204.3090 to appear in New Astronomy.
‘Quantum WDM fermions and gravitation determine the observed galaxy structures’, arXiv:1301.1864.

Minimal galaxy mass from degenerate WDM

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

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

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

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

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

Lightest known compact dwarf galaxy is Willman I: $M_{Willman\ I} = 2.9\ 10^4\ M_\odot$

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

Sterile Neutrinos $\nu \simeq \nu_L + \theta\ \nu_R$

Sterile neutrinos ν_s: named by Bruno Pontecorvo (1968).

WDM ν_s are produced from active neutrinos by mixing.

Mixing angle: $\theta \sim 10^{-3} - 10^{-4}$ is appropriate to produce enough ν_s accounting for the observed total DM.

Smallness of θ makes sterile neutrinos difficult to detect.

Sterile neutrinos can be detected in beta decay and in electron capture (EC) when a ν_s with mass in the keV scale is produced instead of an active ν_a.

The electron spectrum is slightly modified around the mass ($\sim$ keV) of the ν_s in beta decay. Ex: ${}^3H_1 \Longrightarrow {}^3He_2 + e^- + \bar{\nu}$
Available energies for beta decay:
$Q({}^{187}Re) = 2.47$ keV, $\quad Q({}^3H_1) = 18.6$ keV.

For EC: $\quad Q({}^{163}Ho) \simeq 2.5$ keV. ${}^{163}Ho \Longrightarrow {}^{163}Dy^* + \nu$
The nonradiative de-excitation of the Dy^* is observed and is different for ν_s in the keV range than for active ν_a: MARE.

Sterile Neutrinos ν

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

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

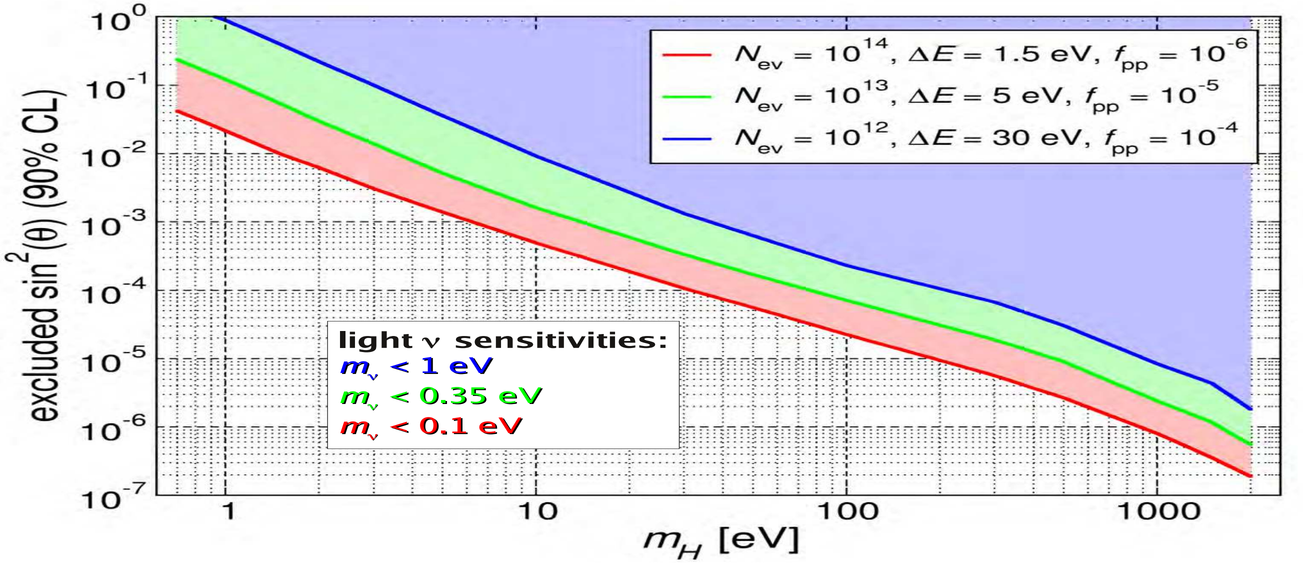
Conclusion: the empty slot of right-handed neutrinos in the Standard Model of particle physics can be filled by keV-scale sterile neutrinos describing the DM.

An appealing mass neutrino hierarchy appears:

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

MARE searchs in Re187 β decay and Ho163 electron capture

MARE sensitivity to heavy neutrinos: ^{187}Re option



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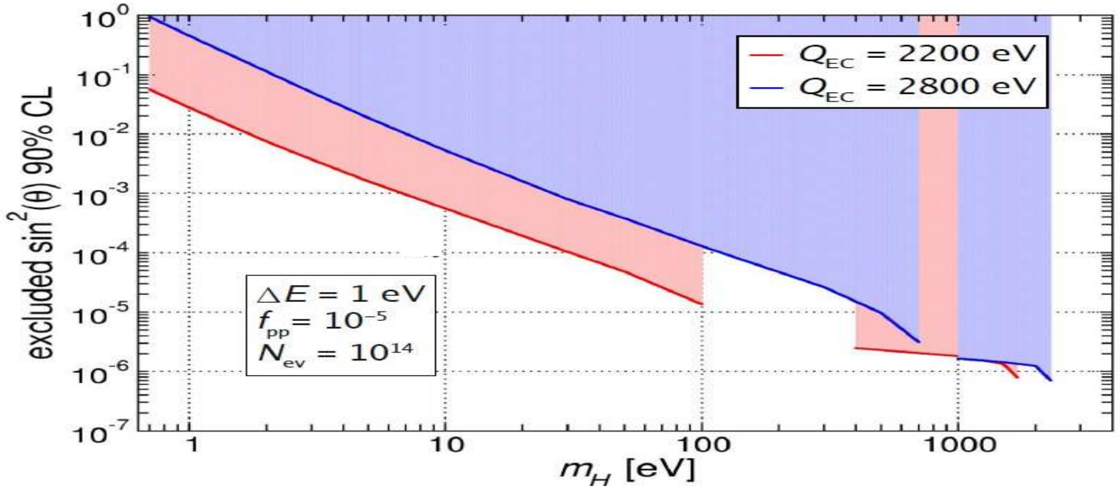
MARE sensitivity to heavy neutrinos: Ho option 2



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Sterile neutrino models

- DW: Dodelson-Widrow model (1994) sterile neutrinos produced by non-resonant mixing from active neutrinos.
- Shi-Fuller model (1998) sterile neutrinos produced by resonant mixing from active neutrinos.
- 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 (FD = thermal fermions):

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

H J de Vega, N Sanchez,
Phys. Rev. D85, 043516 and 043517 (2012).

X-ray detection of DM sterile neutrinos

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

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

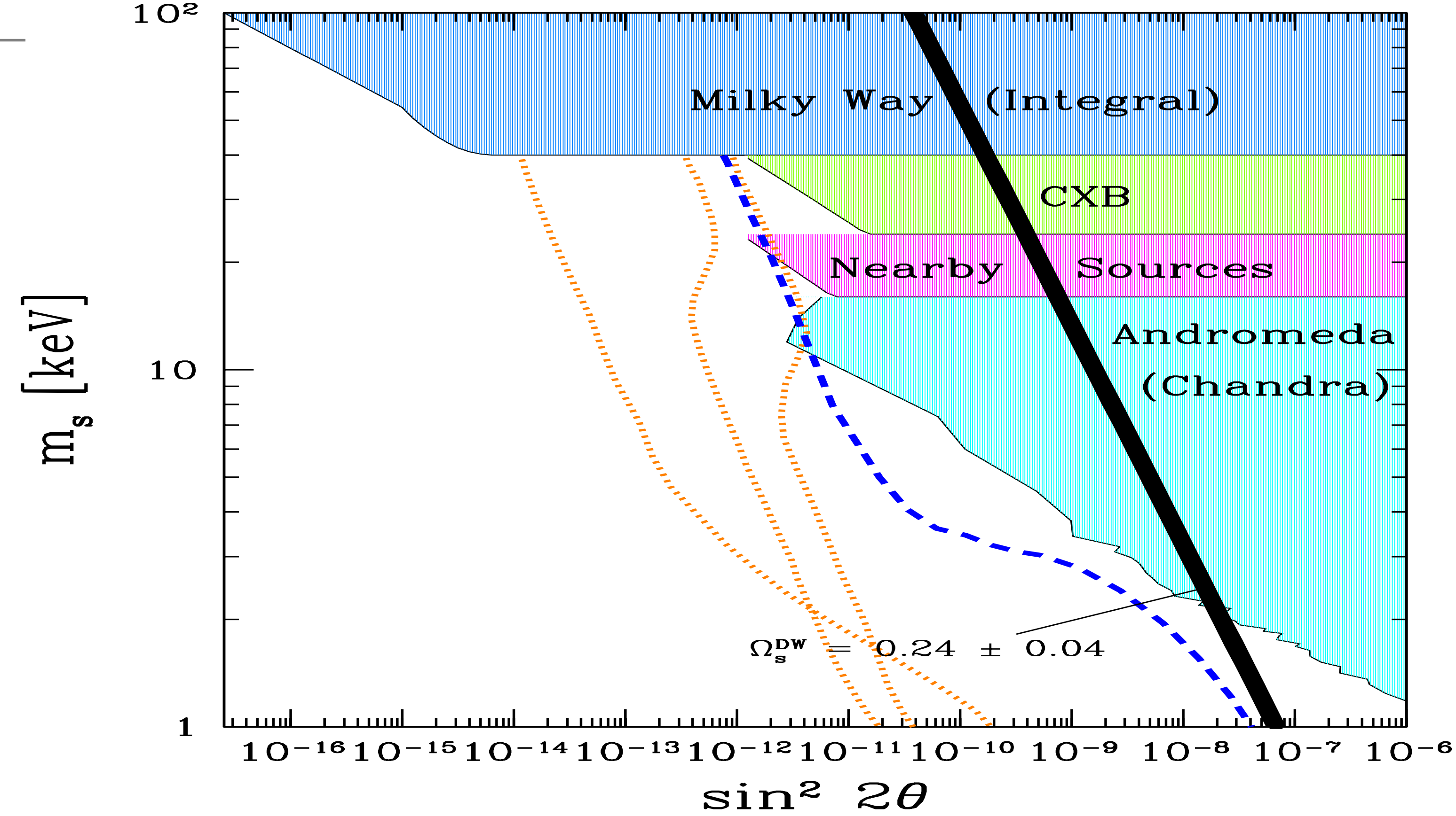
recent review: C. R. Watson et al. JCAP, (2012).

Future observations:

- DM bridge between M81 and M82 ~ 50 kpc. Overlap of DM halos. satellite projects: IXO and Xenia (NASA).
- CMB: WDM decay distorts the blackbody CMB spectrum. The projected PIXIE satellite mission (A. Kogut et al.) can measure WDM sterile neutrino mass.

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

Constraints on the sterile neutrino mass and mixing angle



Dashed = Shi-Fuller model. Dotted = Dodelson-Widrow for fermion asymmetry $L = 0.1,\ 0.01$ and 0.003.

Allowed sterile neutrino region in the right lower corner.

Main difficulty: to distinguish the sterile neutrino decay X-ray from narrow X-lines emitted by hot ions.

Summary: keV scale DM particles

- Reproduce the phase-space density observed in dwarf spheroidal and spiral galaxies (de Vega, Sanchez, MNRAS 2010).
- Fermionic WDM treated quantum mechanically reproduces the main physical galaxy magnitudes: mass, core radius, phase-space density, velocity dispersion, fully consistent with observations and points to a DM particle mass 2 keV (Destri, de Vega, Sanchez, New Astronomy 2012, and 2013).
- The galaxy surface density $\mu_0 \equiv \rho_0 \, r_0$ is universal up to $\pm 10\%$ according to the observations. Its value $\mu_0 \simeq (18 \text{ MeV})^3$ is reproduced by WDM (de Vega, Salucci, Sanchez, New Astronomy, 2012). CDM simulations give 1000 times the observed value of μ_0 (Hoffman et al. ApJ 2007).

Summary: keV scale DM particles

- Alleviate the CDM satellite problem (Avila-Reese et al. 2000, Götz & Sommer-Larsen 2002, Markovic et al. JCAP 2011) and the CDM voids problem (Tikhonov et al. MNRAS 2009).
- Velocity widths in galaxies from 21cm HI surveys. ALFALFA survey clearly favours WDM over CDM. Papastergis et al. ApJ 2011, Zavala et al. ApJ 2009
- 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. PRL (2009), P. Blasi, P. D. Serpico PRL (2009).
- Highlights and conclusions of the Chalonge Meudon Workshop 2011: Warm dark matter in the galaxies, arXiv:1109.3187 and the 16th Paris Cosmology Colloquium 2011 arXiv:1203.3562, H. J. de V., N. G. S.

Future Perspectives

DM properties from galaxy observations.
keV scale DM particles are strongly favoured.
Determination of DM properties (mass, T_d) from galaxy data confronted with theory.

WDM simulations showing substructures, galaxy formation and evolution including quantum dynamical evolution for the WDM cores. Quantum pressure must be included !

Sterile neutrinos ? Other particle in the keV mass scale?
Chandra, Suzaku, XMM, X-ray data: keV mass DM decay?

Neutrinos mass hierachy: active $\sim$ meV, light sterile $\sim$ eV, WDM sterile $\sim$ keV, unstable sterile $\sim$ MeV....

Bounds from MARE on sterile neutrino mass and θ.
Could KATRIN join the search of keV sterile neutrinos?

Ideally: make a beta decay or EC experiment dedicated to search sterile neutrinos with mass around 2 keV.

Richard P. Feynman foresaw the necessity to include quantum physics in simulations in 1981

“I’m not happy with all the analyses that go with just the classical theory, because nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.”

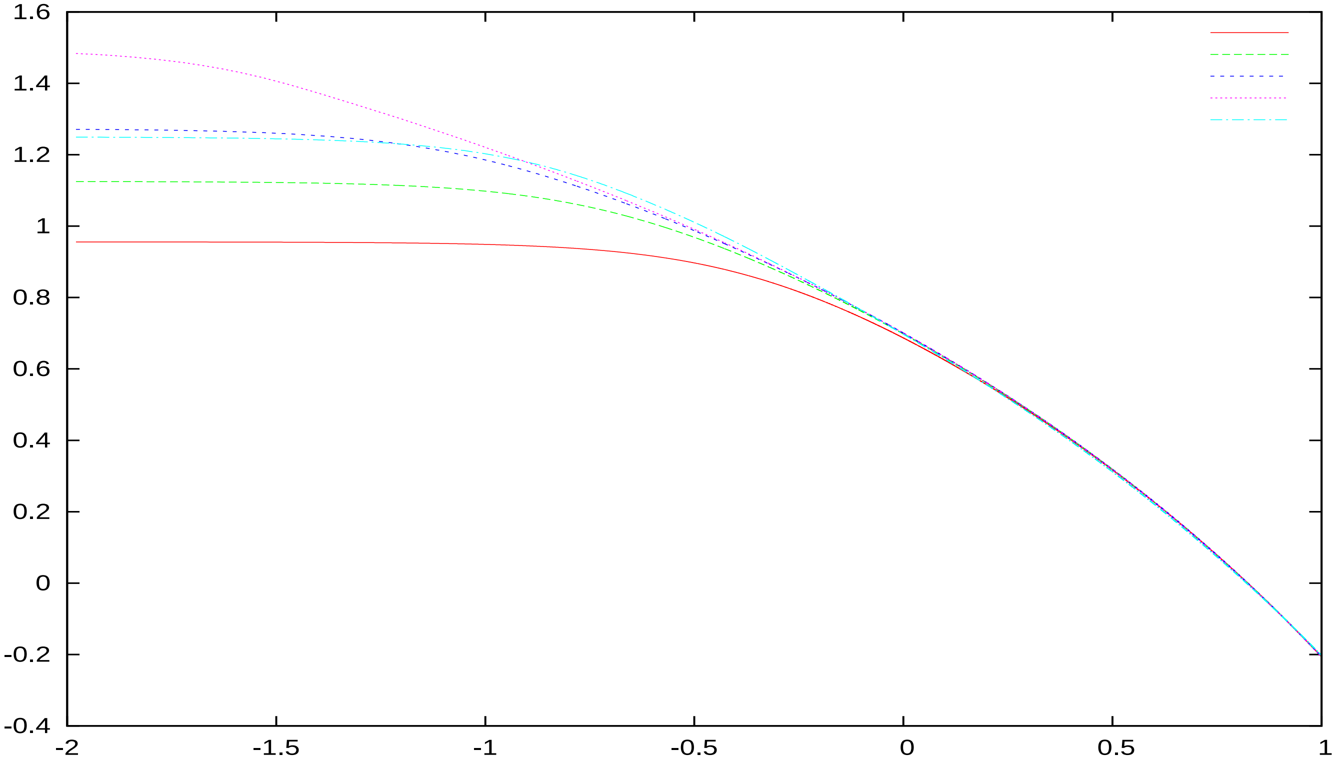
THANK YOU VERY MUCH

FOR YOUR ATTENTION!!

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. $\log(R/h\ \mathrm{Mpc})$ 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.

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 % $\quad , \quad$ 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.

Galaxy Density Profiles: Cores vs. Cusps

Astronomical observations always find cored profiles.
Selected references:
J. van Eymeren et al. A&A (2009), M. G. Walker, J.Peñarrubia,ApJ(2012).N.Amorisco,N.Evans,MNRAS(2012).

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

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

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

N-body simulations for WDM : quantum physics needed for fermionic DM !!! (Destri, de Vega, Sanchez, 2012)

CDM simulations give a precise value
for the concentration $\equiv R_{virial}/r_0$.

CDM concentrations disagree with observed values.