Fermionic Warm Dark Matter and galaxy structure in agreement with observations in the ΛWDM Standard Model

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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:

- Cold Dark Matter: CDM, WIMPS, $m \sim 1 - 1000$ GeV.
  IN BIG TROUBLE.
- Warm Dark Matter: WDM, sterile neutrinos $m \sim 1$ keV.
  THE ANSWER !

DM particles decouple due to the universe expansion, their distribution function freezes out at decoupling.
Early decoupling: $T_d \sim 100$ GeV

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 small linear 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.

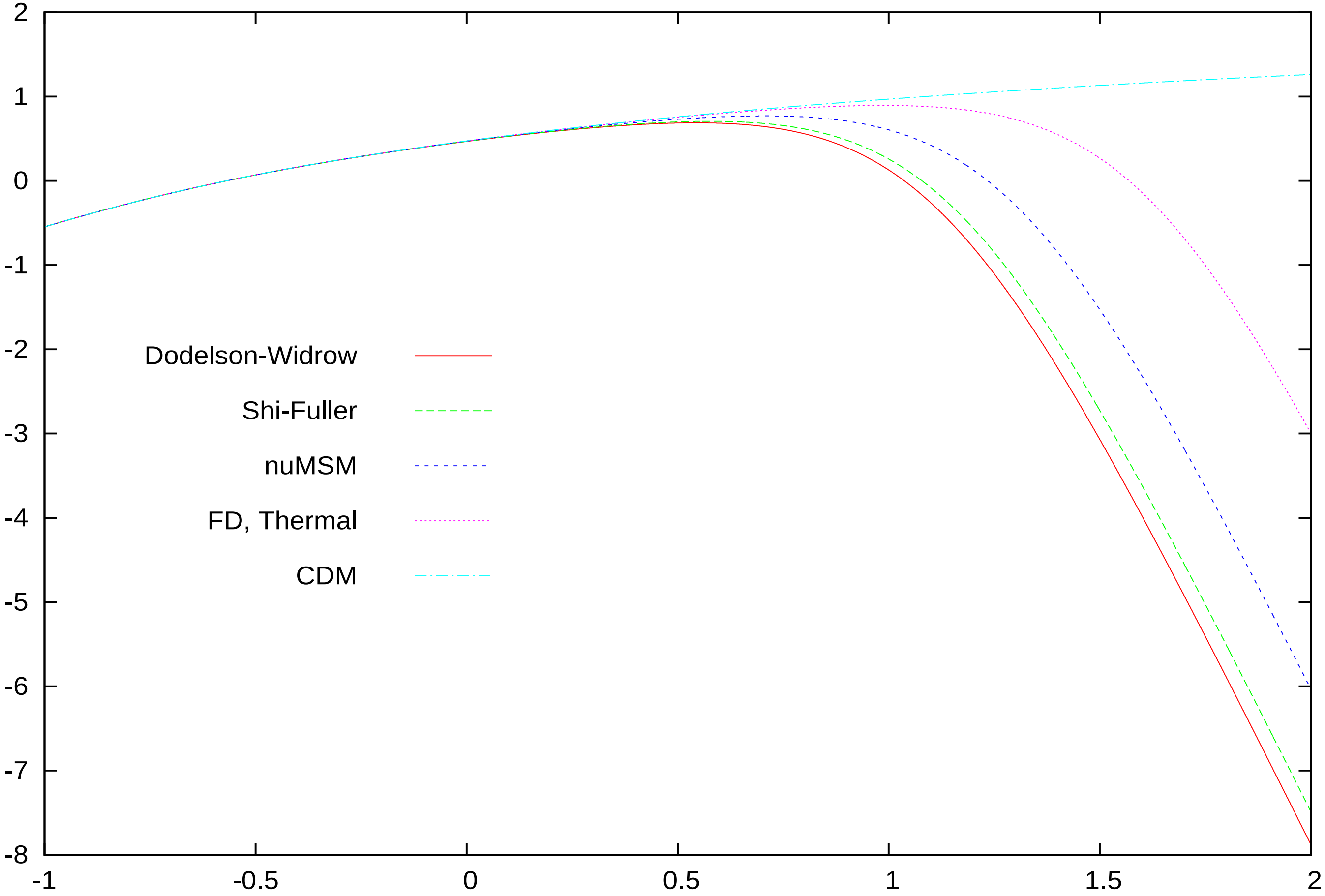
N-body CDM simulations fail to produce the observed structures for small scales less than some kpc.

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 $\Delta^2(k)$: first ingredient in galaxy formation.

Linear primordial power spectrum $\Delta^2(k)$ vs. k Mpc $/h$



$\log_{10} \Delta^2(k)$ vs. $\log_{10}[k \text{ Mpc}/h]$ for a physical mass of 2.5 keV in four different WDM models and in CDM. WDM cuts $\Delta^2(k)$ on small scales. $r \lesssim 73 \, (\text{keV}/m)^{1.45}$ kpc/h.
CDM and WDM are identical for CMB.

WDM Primordial Power Spectrum

The WDM Primordial Power Spectrum is obtained solving the linear Boltzmann-Vlasov equations.

We define the transfer function ratio $T^2(k) \equiv \frac{\Delta^2_{wdm}(k)}{\Delta^2_{cdm}(k)}$

Reproduced by the analytic formula $T^2(k) = \left[1 + \left(\frac{k}{\kappa}\right)^a\right]^{-b}$

a and b are independent of the WDM particle mass m.

κ scales with m. In our best fit:

$$a = 2.304 \; , \quad b = 4.478 \; , \quad \kappa = 14.6 \; (m_{FD}/\text{keV})^{1.12} \; h/\text{Mpc}$$

At the wavenumber $k_{1/2} : \; T^2(k_{1/2}) = 1/2$ and

$$k_{1/2} = 6.72 \; (m_{FD}/\text{keV})^{1.12} \; h/\text{Mpc}$$

The characteristic length scale is

$$l_{1/2} = 1/k_{1/2} = 207 \; \text{kpc} \; (\text{keV}/m_{FD})^{1.12}$$

This scale reproduces the sizes of the DM galaxy cores when the WDM mass is in the keV scale !!

WDM free streaming scale

The scale $l_{1/2}$ is similar but more precise than the free streaming scale (or Jeans' scale):

$$r_{Jeans} = 210\,\mathrm{kpc}\,\frac{\mathrm{keV}}{m_{FD}}\,\left(\frac{100}{g_d}\right)^{\frac{1}{3}}\;,$$

$g_d =$ 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 which agrees with the observed structures in galaxies !!

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. Including baryons do not cure this serious problem. 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. Adding by hand strong enough feedback from baryons does not eliminate cusps (F. Marinacci et al., arXiv:1305.5360).

Axions in the 10^{-22} eV range are ruled out as dark matter

Hot Dark Matter (particles lighter than the eV) are ruled out because their free streaming length is too large $\gtrsim$ Mpc and hence galaxies are not formed.

A Bose-Einstein condensate of light scalar particles evades this argument because of the quantum nature of the BE condensate. $r_{Jeans} \sim 50$kpc implies $m \sim 10^{-22}$eV.

The phase-space density $Q = \rho/\sigma^3$ decreases during structure formation: $Q_{today} < Q_{primordial} \propto m^4$.
Computing Q for a DM Bose-Einstein condensate we derived lower bounds on the DM particle mass m using the data for Q in dwarf galaxies:

$$m \geq 0.227\,\mathrm{keV}\,\left(\frac{200}{g_d}\right)^{5/3}$$

Axions with $m \sim 10^{-22}$ eV are ruled out as DM candidates.

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

Summary Warm Dark Matter, WDM: $m \sim$ keV

- Large Scales, structures beyond ~ 100 kpc: WDM and CDM yield identical results which agree with observations
- Intermediate Scales: WDM give the correct abundance of substructures.
- Inside galaxy cores, below ~ 100 pc: N-body classical physics simulations are incorrect for WDM because of important quantum effects.
- Quantum calculations (Thomas-Fermi) give galaxy cores, galaxy masses, velocity dispersions and densities in agreement with the observations.
- Direct Detection of the main WDM candidate: the sterile neutrino. Beta decay and electron capture. ^{3}H, Re, Ho.

So far, not a single valid objection arose against WDM.
Baryons (=16%DM) expected to give a correction to WDM

Quantum physics in Galaxies

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

$d =$ mean distance between particles, $v =$ mean velocity

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

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

Observed values: $2 \times 10^{-3} \, \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}} < \mathcal{R} < 1.4 \, \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}}$

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).
No quantum effects in CDM: $m \gtrsim$ GeV $\Rightarrow \mathcal{R} \lesssim 10^{-8}$

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

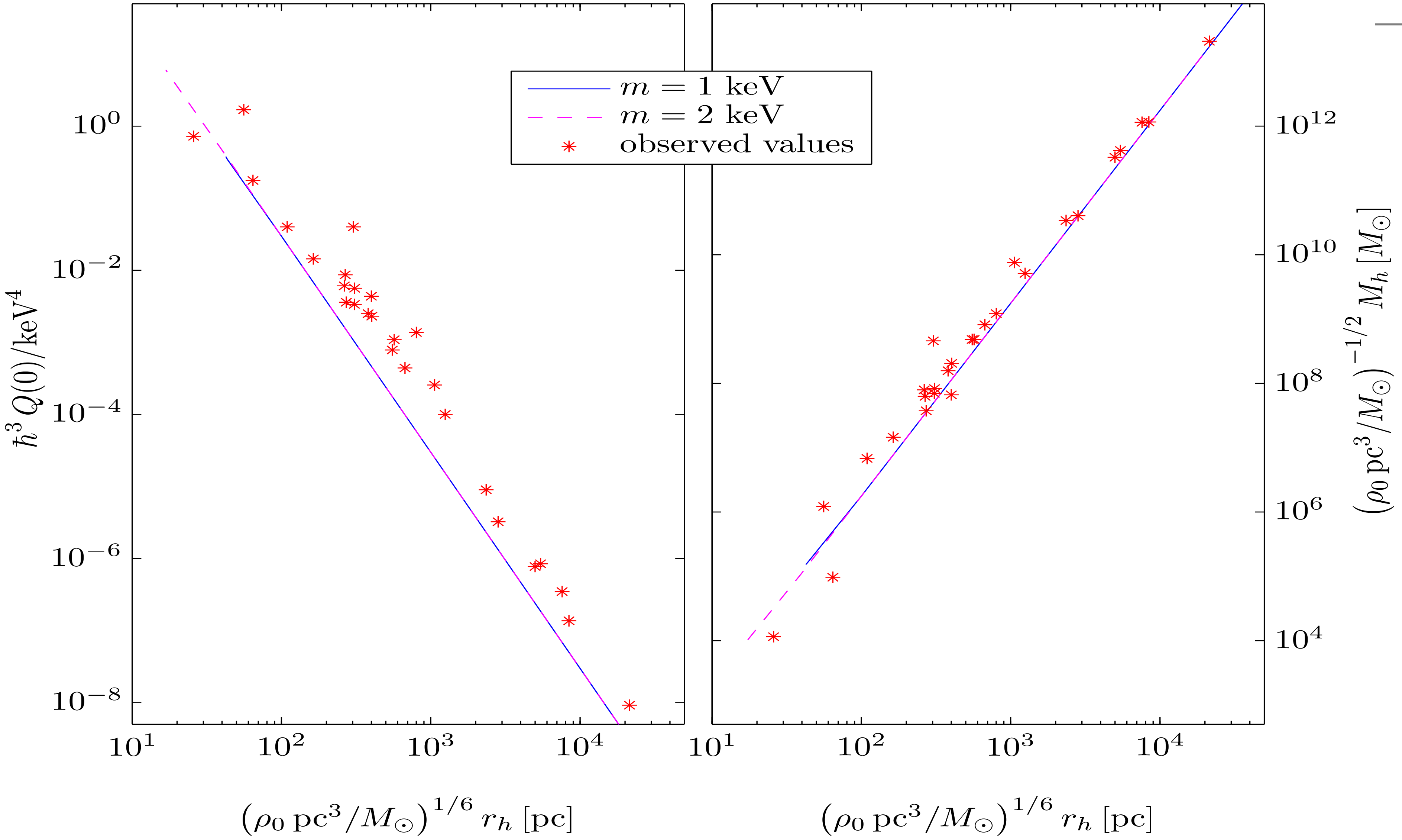
Density $\rho(r)$ and pressure $P(r)$ in terms of the distribution function $f(E)$:

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

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

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

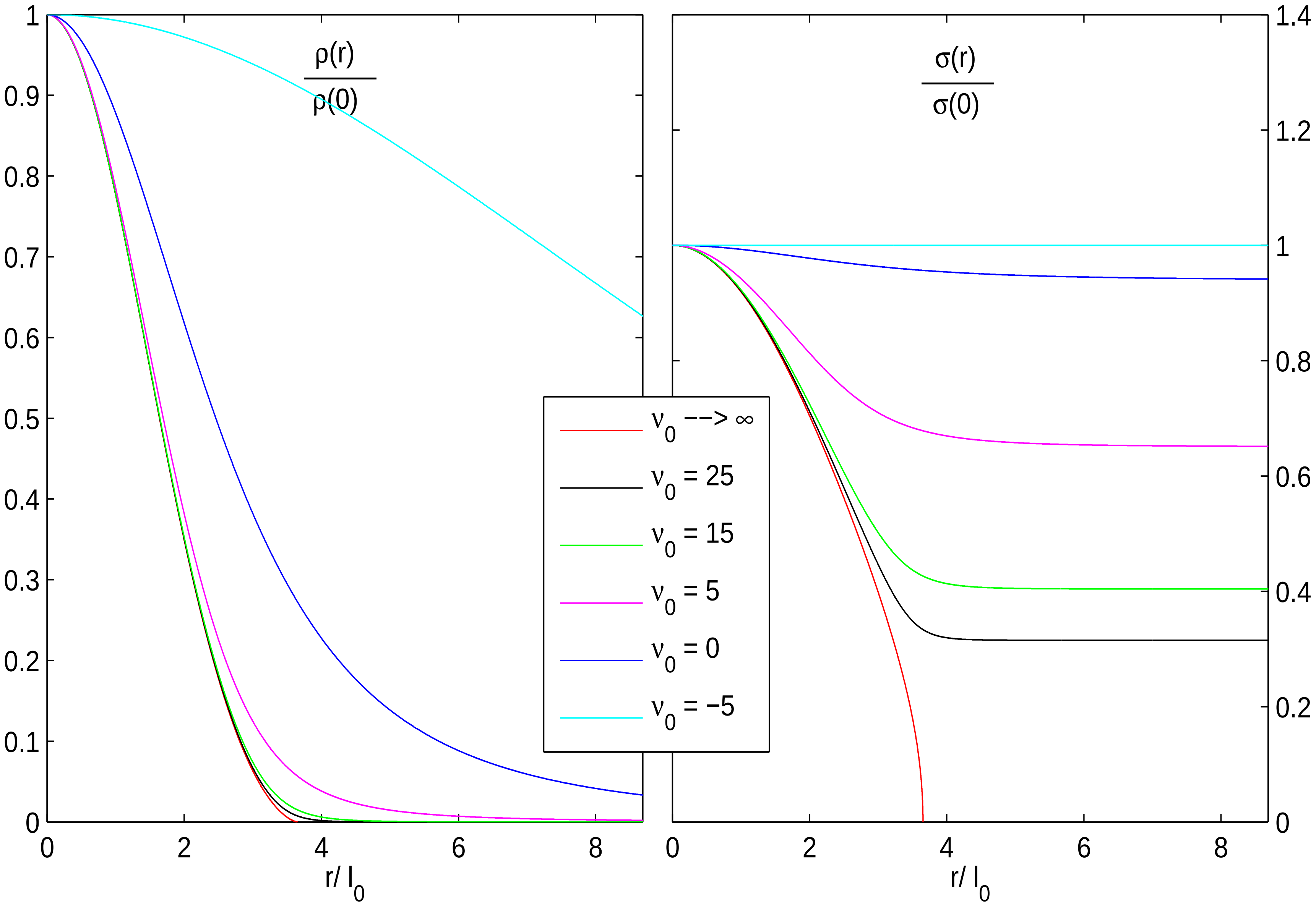
Q vs. halo radius. Galaxy observations vs. Thomas-Fermi



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

Density and velocity profiles from Thomas-Fermi

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



Galaxy data vs. Thomas-Fermi

Mass, halo radius, velocity dispersion and central density from a broad variety of galaxies: ultracompact galaxies to giant spirals, Willman 1, Segue 1, Canis Venatici II, Coma-Berenices, Leo II, Leo T, Hercules, Carina, Ursa Major I, Draco, Leo I, Sculptor, Boötes, Canis Venatici I, Sextans, Ursa Minor, Fornax, NGC 185, NGC 855, NGC 4478, NGC 731, NGC 3853, NGC 499 and a large number of spiral galaxies.

Phase-Space distribution function $f(E/E_0)$: Fermi-Dirac ($F(x) = \frac{1}{e^x+1}$) and out of equilibrium sterile neutrinos give similar results.

$E_0 =$ effective galaxy temperature (energy scale).

E_0 turns to be 10^{-3} ^{o}K $< E_0 <$ 50 ^{o}K

colder = ultracompact, warmer = large spirals.

$E_0 \sim m \ < v^2 >_{\rm observed}$ for $m \sim 2$ keV.

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 2.5 keV.

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

Thomas-Fermi approach works in the classical (Boltzmann) regime too: we always obtain cores with observed sizes.

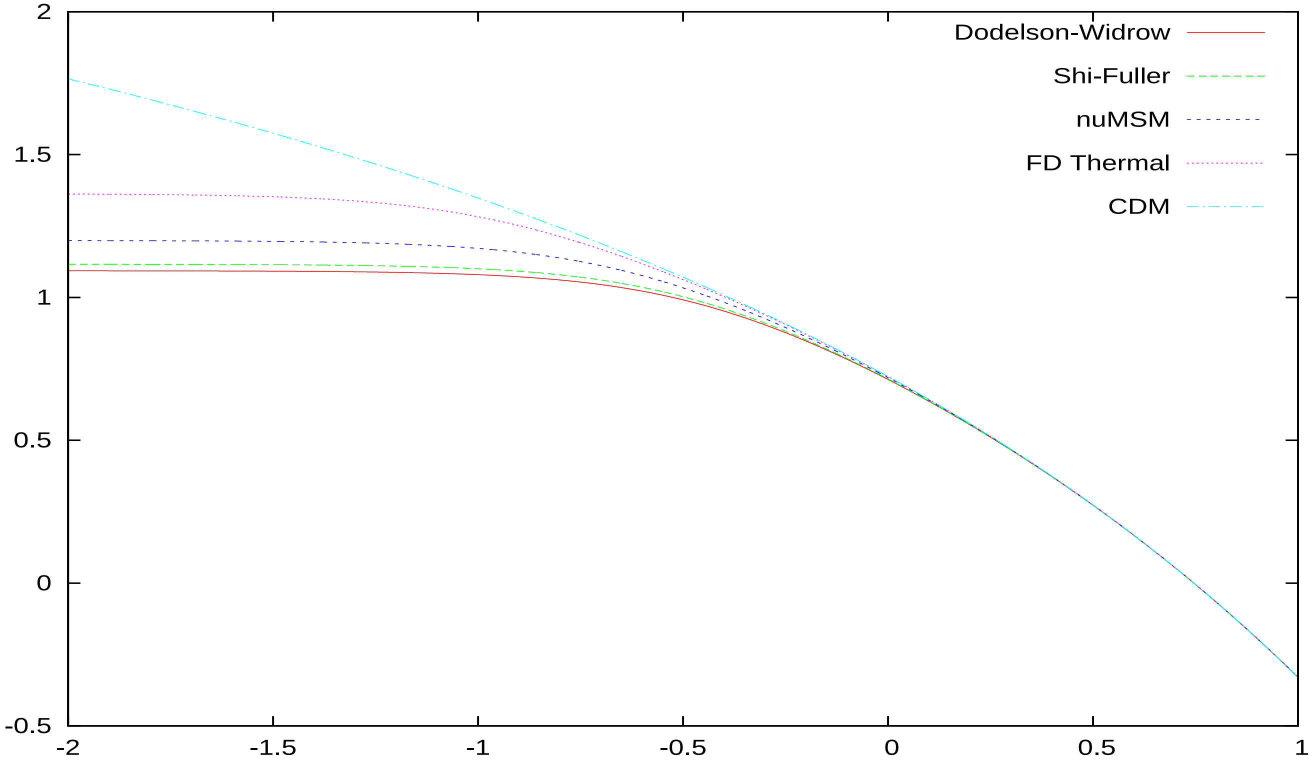
Fermionic WDM treated quantum mechanically is able to reproduce the observed galaxies.

C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:1204.3090, New Astronomy **22**, 39 (2013) and arXiv:1301.1864, Astroparticle Physics, **46**, 14 (2013).

The expected overdensity

The expected overdensity within a comoving 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.



$\log_{10} \sigma^2(R, z=0)$ vs. $\log_{10}[R\; h/\mathrm{Mpc}]$ for $m = 2.5$ keV in four different WDM models and in CDM.

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

Redshift dependence and Relative overdensity D(R)

$\sigma(M,z) = \frac{g(z)}{z+1}\,\sigma(M,0)$ during the MD/Λ dominated era.

$g(z)$: the effect of the cosmological constant. $g(z)$ is a hypergeometric function ${}_2F_1$, $g(0) = 0.76$, $g(\infty) = 1$

We introduce the relative overdensity: $D(R) \equiv \frac{\sigma^2_{WDM}(R,z)}{\sigma^2_{CDM}(R,z)}$

(z dependence cancels out).

Characteristic scale below which structures are suppresed in WDM compared with CDM: $R_{1/2}$ where $D(R_{1/2}) = 1/2$,

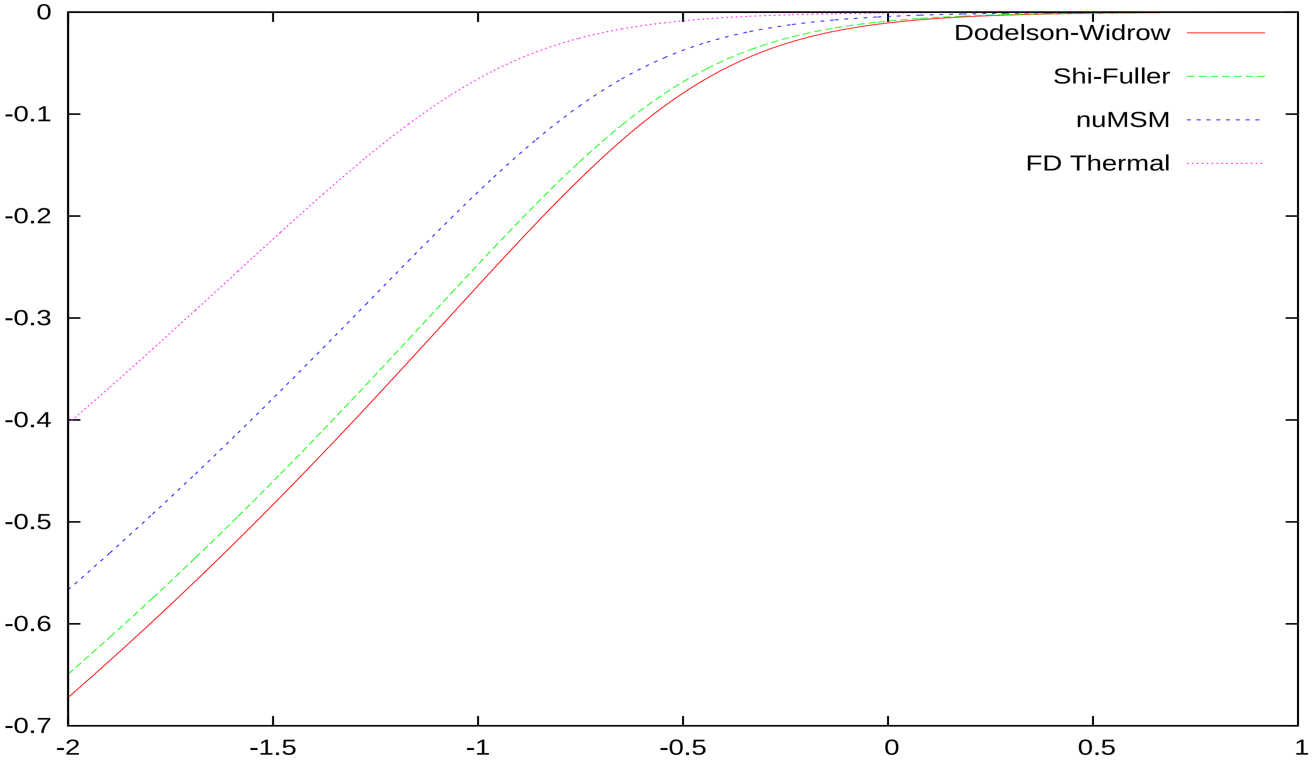
$$R_{1/2} = 73.1 \;\frac{\text{kpc}}{h}\; \left(\frac{\text{keV}}{m_{FD}}\right)^{1.45}$$

$D(R)$ can be reproduced by the simple formula:

$$D(R) = \left[1 + \left(2^{1/\beta} - 1\right)\left(\frac{R_{1/2}}{R}\right)^{\alpha}\right]^{-\beta}$$

$\alpha \simeq 2.2 \quad , \quad \beta \simeq 0.17 \quad , \quad 2^{1/\beta} - 1 \simeq 58$

The Relative Overdensity



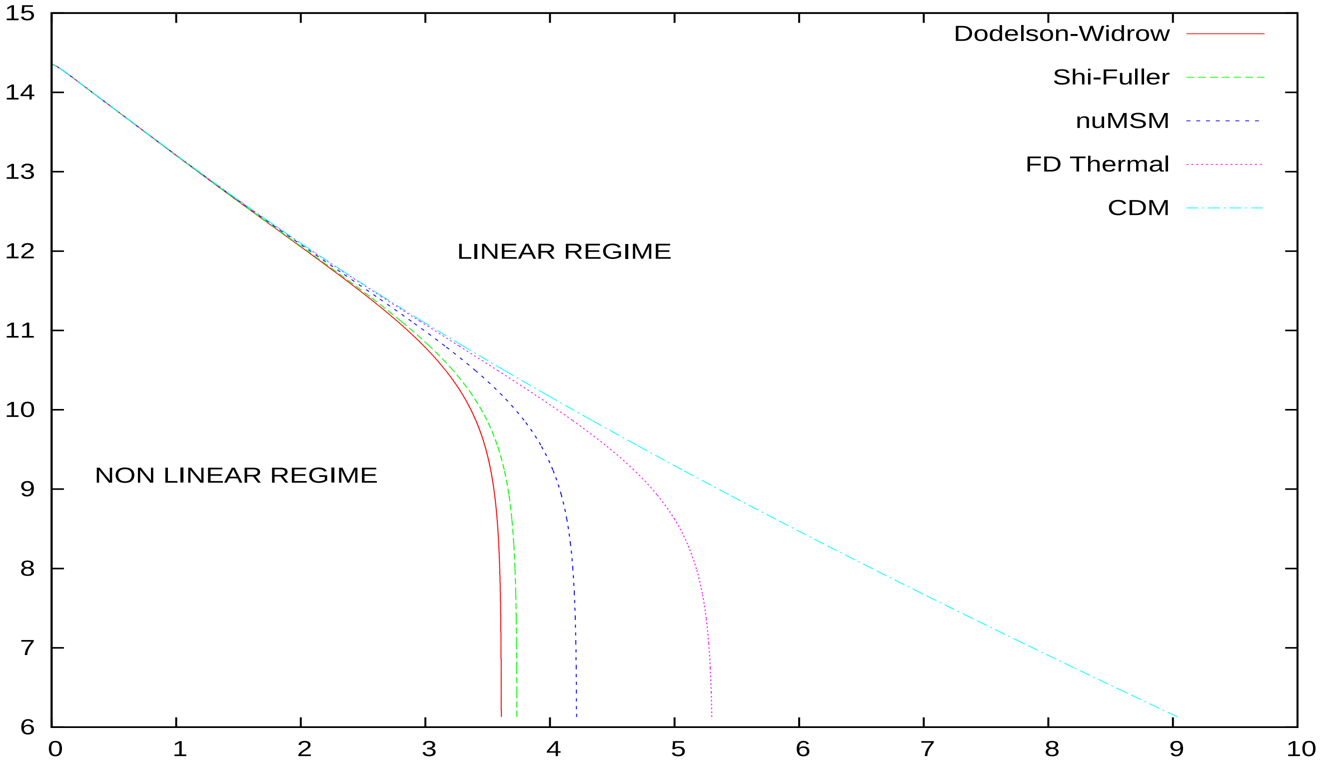
$\log_{10} D(R)$ vs. $\log_{10}[R\,h/\mathrm{Mpc}]$.

The scales where practically all the CDM structures are suppressed in WDM and the scales where both CDM and WDM give the same structures are separated by a factor ~ 500. This slow transition is due to the smallness of the exponent $\alpha\,\beta \simeq 0.37$.

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 can form earlier.



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

Relative overdensity D(R) and Press-Schechter approach

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

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

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

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

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

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

Sterile Neutrinos $\nu_s \simeq \nu_R + \theta\, \nu_L$

Sterile neutrinos ν_s: named by Bruno Pontecorvo (1968).
Singlets under all SM symmetries.
Do not interact weak, neither EM, nor strongly.

WDM ν_s can be produced from active neutrinos by mixing.

Mixing angles: $\theta \sim 10^{-3} - 10^{-4}$ (depending on the model) are 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_e.

Beta decay: the electron spectrum is slightly modified at energies around the mass ($\sim$ keV) of the ν_s.

$$^3H_1 \Longrightarrow {}^3He_2 + e^- + \bar{\nu}_e \quad , \quad {}^{187}Re \Longrightarrow {}^{187}Os + e^- + \bar{\nu}_e .$$

The electron energy spectrum is observed.

Electron Capture and Sterile Neutrinos

Electron capture: $^{163}Ho + e^- \Longrightarrow {}^{163}Dy^* + \nu_e$

The nonradiative de-excitation of the Dy^* is observed and is different for ν_s in the keV range than for active ν_e.

Available energies:

$Q(^{187}Re) = 2.47$ keV, $Q(^3H_1) = 18.6$ keV, $Q(^{163}Ho) \simeq 2.5$ keV.

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

Present experiments searching the small active neutrino mass also look for sterile neutrinos in the keV scale:

MARE (Milan, Italy), Rhenium beta decay and Holmiun EC.

KATRIN (Karlsruhe, Germany), Tritium beta decay.

ECHo (Heidelberg, Germany), Holmiun EC.

Project 8, (Seattle, USA) Tritium beta decay (still in project).

Sterile neutrino models

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

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

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

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

X-ray detection of DM sterile neutrinos

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

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

Future observations:

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

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

Direct searches of CDM particles

All direct searches of wimps look for $m \gtrsim 1$ GeV.

Past, present and future reports of signals in such wimp experiments cannot be due to DM detection because the DM particle mass is in the keV scale.

The inconclusive signals in such experiments should be originated by other kinds of phenomena.

Contradictions between supposed detection signals in DAMA, CDMS-II, CoGeNT, CRESST, XENON100.

CONCLUSION: These signals are unrelated to DM.

e^+ and $\bar{p}$ excess in cosmic rays reported by Pamela and Fermi may be explained by astrophysics: P. L. Biermann et al. PRL (2009), P. Blasi, P. D. Serpico PRL (2009).

AMS02: precise measure of the positron fraction in Galactic cosmic rays (CR) (PRL 2013) that increases with energy. Blum, Katz & Waxman (arXiv:1305.1324) show that this is consistent with positron production by the collision of high energy primary CR with the interstellar medium.

Sterile neutrinos and CMB fluctuations

CMB data give the effective number of neutrinos, $\mathrm{N_{eff}}$.

$\mathrm{N_{eff}}$ is related in a subtle way to the number of active neutrinos (3) plus the number of sterile neutrinos.

Planck result: $\mathrm{N_{eff}} = 3.5 \pm 0.5$ $(95\%$;P+WP+highL+H_0+BAO)

Entropy conservation determines the contributions to $\mathrm{N_{eff}}$.

WDM sterile neutrino contribution at recombination

$\Delta N^{WDM} = \left(\frac{T_d}{T_{rc}}\right)^4 = \left[\frac{g_{rc}}{g(T_d)}\right]^{4/3}$. At recombination $g_{rc} = 29/4$.

WDM decouples early at T_d beyond the Fermi scale

The number of UR degrees of freedom at decoupling $g(T_d)$ includes all SM particles and probably beyond.

$g_{SM} = 427/4 \quad , \quad g_{MSSM} = 915/4$,

$\Delta N^{WDM}_{SM} = 0.02771\ldots \quad , \quad \Delta N^{WDM}_{MSSM} = 0.01003\ldots$

Too small to be measurable at present !

Planck results cannot provide information about WDM.

Besides, Planck results are **compatible** with one or two eV sterile neutrinos (see e. g. G. Steigman, 1303.0049).

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
- Highlights and Conclusions of the Chalonge Meudon Workshop 2011: Warm dark matter in the galaxies, arXiv:1109.3187, the 15th Paris Cosmology Colloquium 2011, arXiv:1203.3562, HJdeV, NGS, and the Chalonge Meudon Workshop 2012, arXiv:1305.7452, PLB, HJdeV, NGS. 16th Paris Cosmology Colloquium 2012, arXiv:1307.1847 HJdeV, M.C. Falvella, NGS.

Future Perspectives

WDM particle models must explain the baryon asymmetry of the universe. 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....

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

WDM simulations should be performed matching semiclassical Hartree-Fock (Thomas-Fermi) dynamics in regions where $Q/m^4 > 0.1$ with classical evolution in regions where $Q/m^4 \ll 1$. Not easy but unavoidable!

Future Perspectives: Detection!

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

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

Direct detection of steriles in Lab:

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

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

Calorimetric techniques seem well suited.

Best nuclei for study:

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

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.”

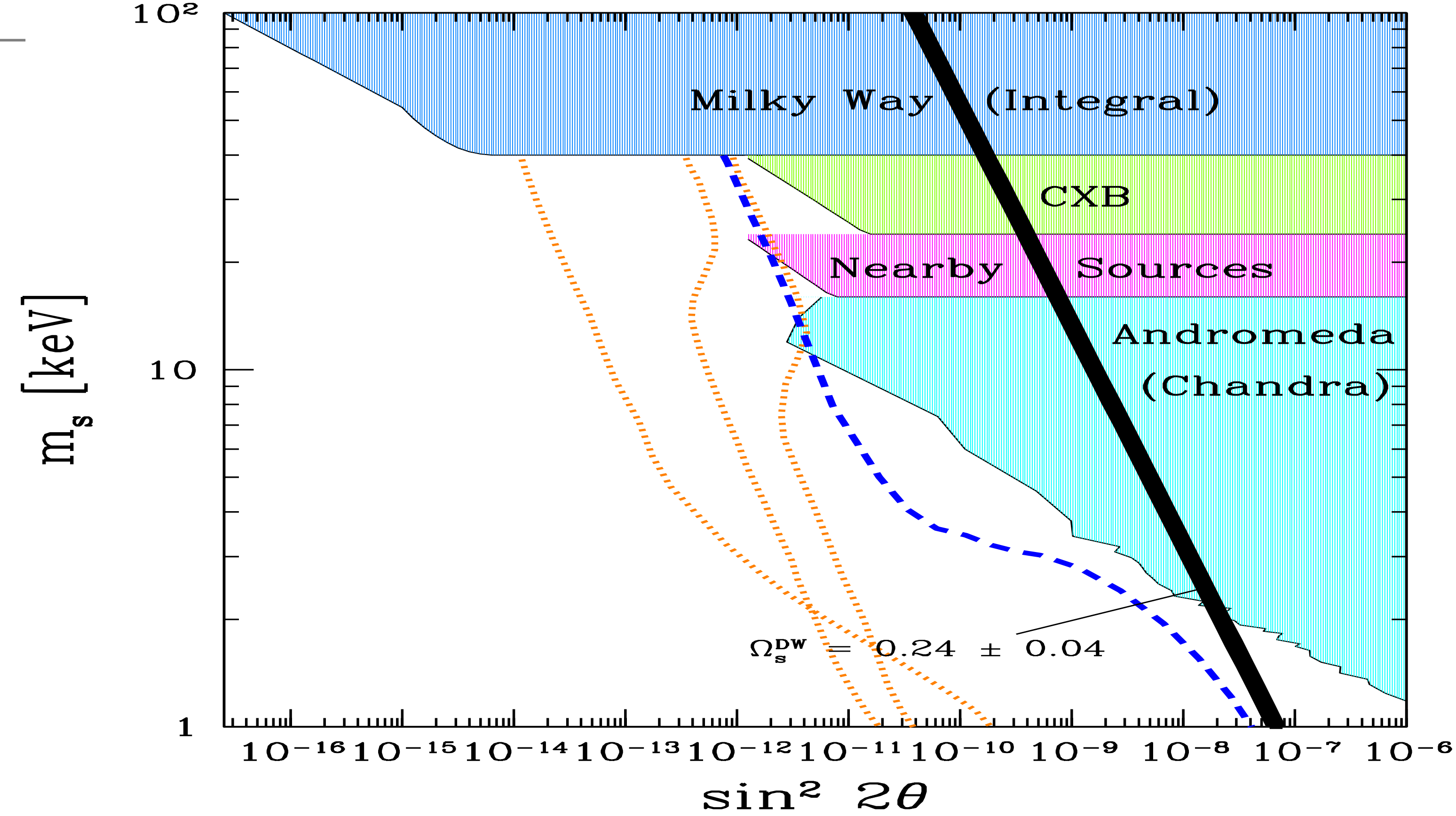
Feynman again:

“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong. R. P. Feynman”

THANK YOU VERY MUCH

FOR YOUR ATTENTION!!

Constraints on the sterile neutrino mass and mixing angle

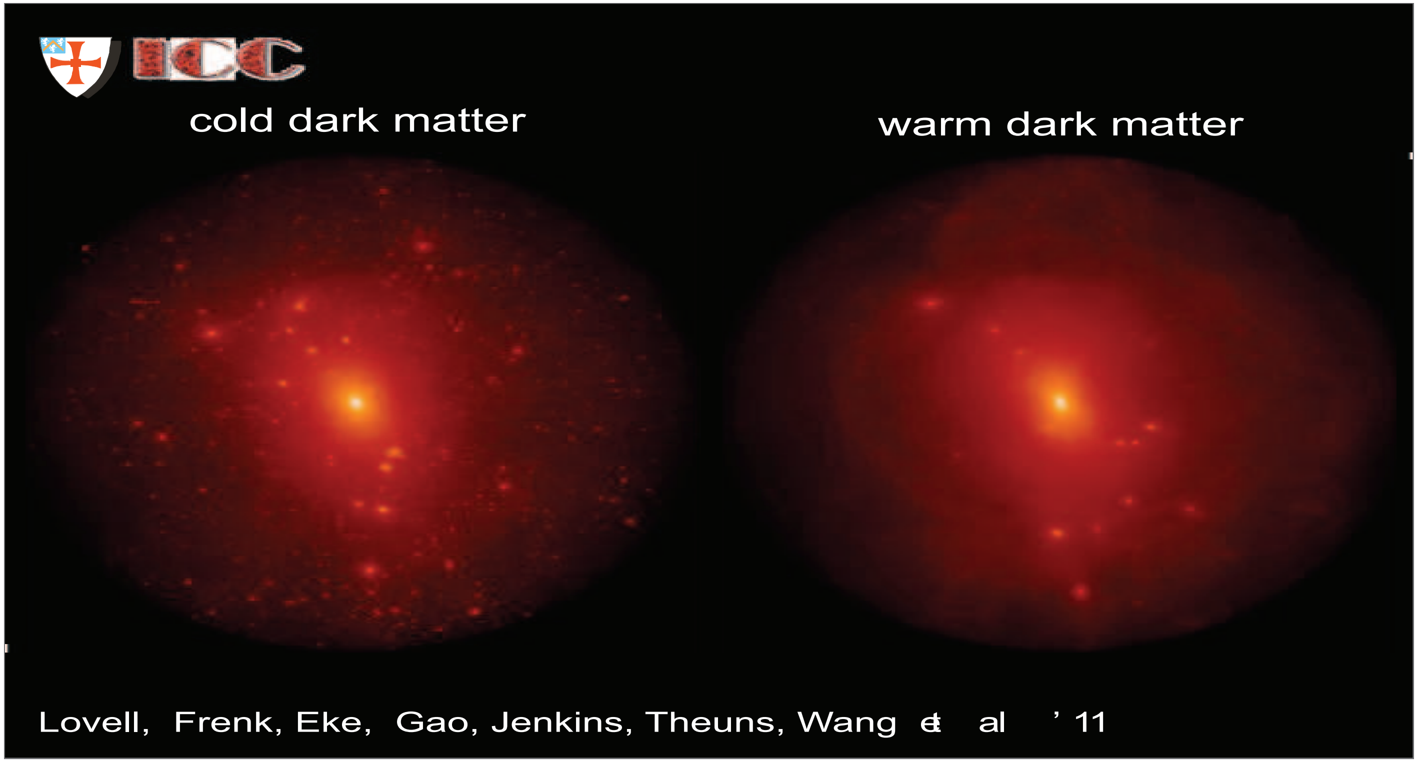


Dashed = Shi-Fuller model. Dotted = Dodelson-Widrow for fermion asymmetry $L = 0.1,\ 0.01$ and 0.003.

Allowed sterile neutrino region in the right lower corner.

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

N-body WDM Simulations: substructure formation



Lovell, Frenk, Eke, Gao, Jenkins, Theuns, Wang et al '11

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.