

# FROM COLD TO WARM DARK MATTER IN THE STANDARD MODEL OF THE UNIVERSE AND GALAXY FORMATION

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**QCD at Cosmic Energies - V**

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# Standard Cosmological Model: DM + $\Lambda$ + Baryons + Radiation

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

# Standard Cosmological Model: $\Lambda$ CDM $\Rightarrow$ $\Lambda$ WDM

Dark Matter +  $\Lambda$  + 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  $\alpha$  Forest Observations and X ray data
- Hubble Constant and Age of the Universe Measurements
- Properties of Clusters of Galaxies
- Galaxy structure explained by WDM

# Dark Matter Particles

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

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

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

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

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

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

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

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

# CDM free streaming scale

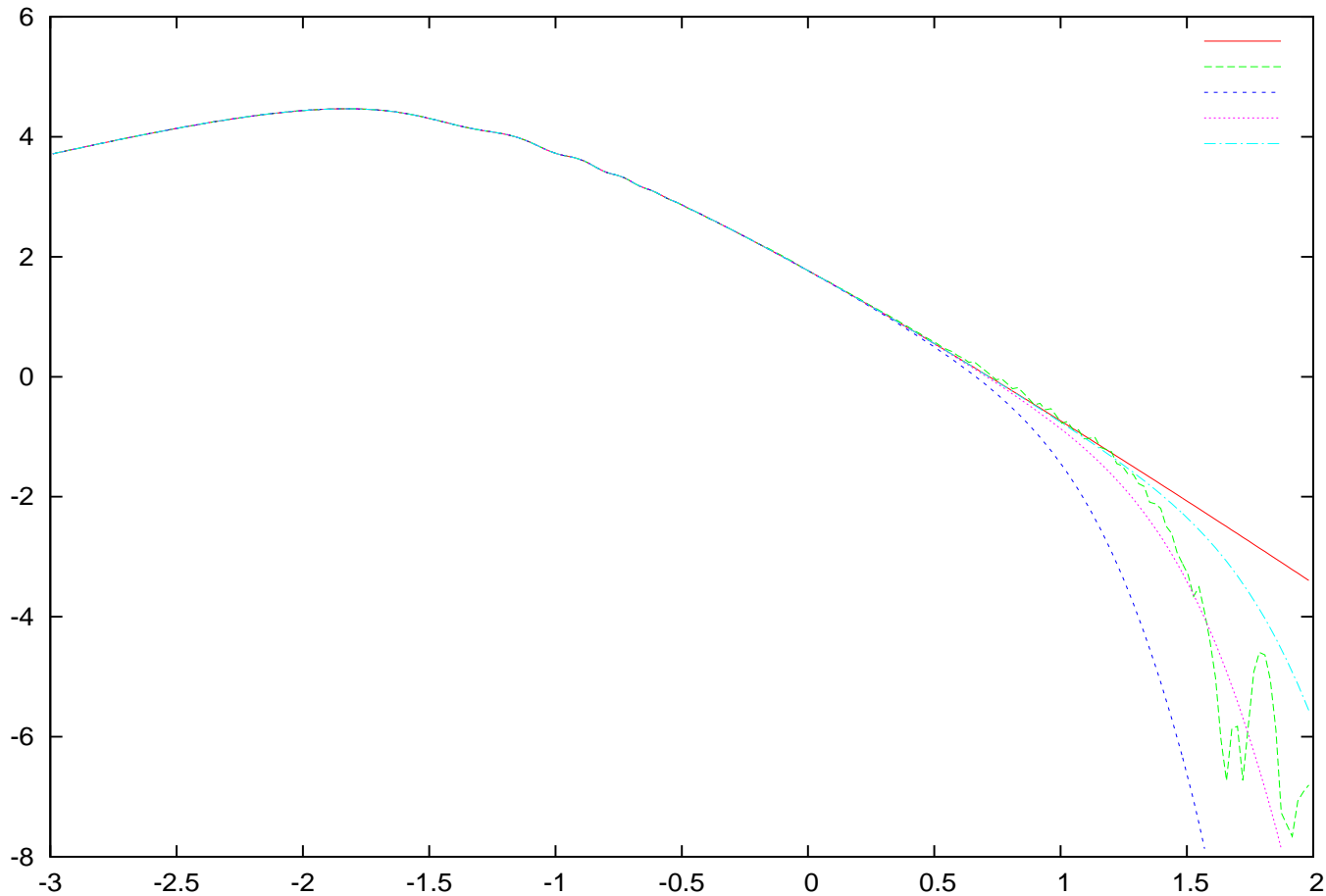
For CDM particles with  $m \sim 100 \text{ GeV}$ :  $r_{lin} \sim 0.1 \text{ pc}$

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

This has been **explicitly verified** by all CDM simulations but **never observed** in the sky.

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

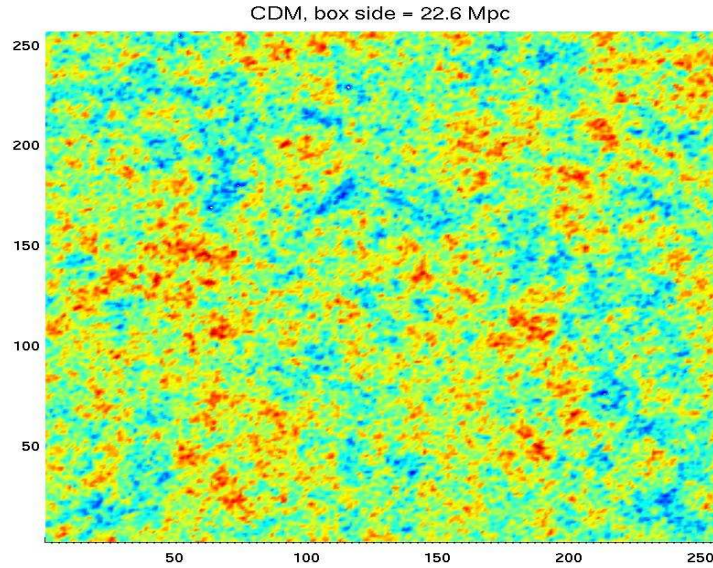
# Linear primordial power today $P(k)$ vs. $k$ Mpc $h$



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

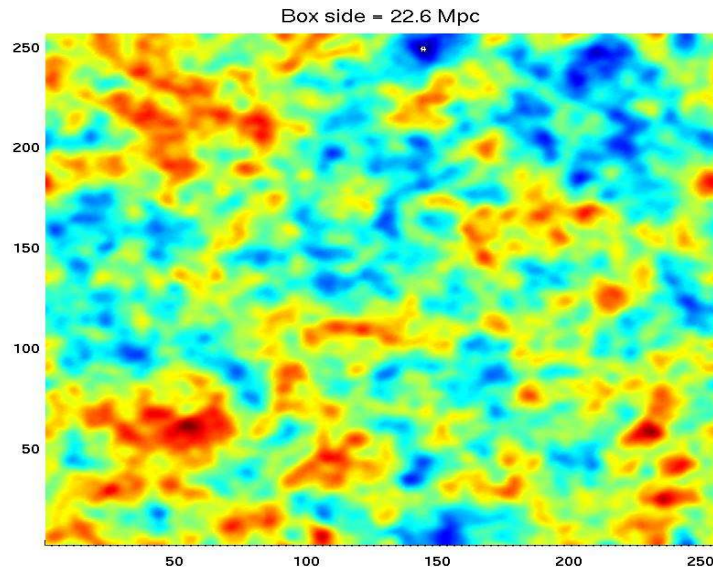
$$r \lesssim 100 (\text{keV}/m)^{4/3} \text{ kpc}$$

# WDM vs. CDM linear fluctuations today

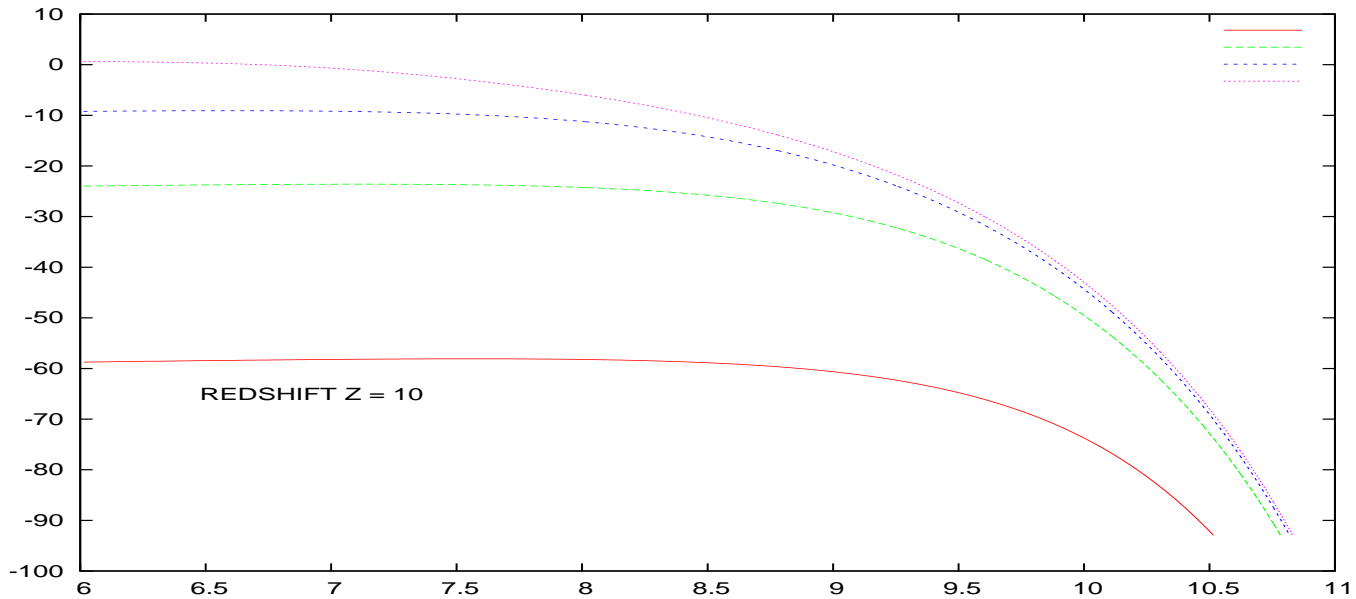
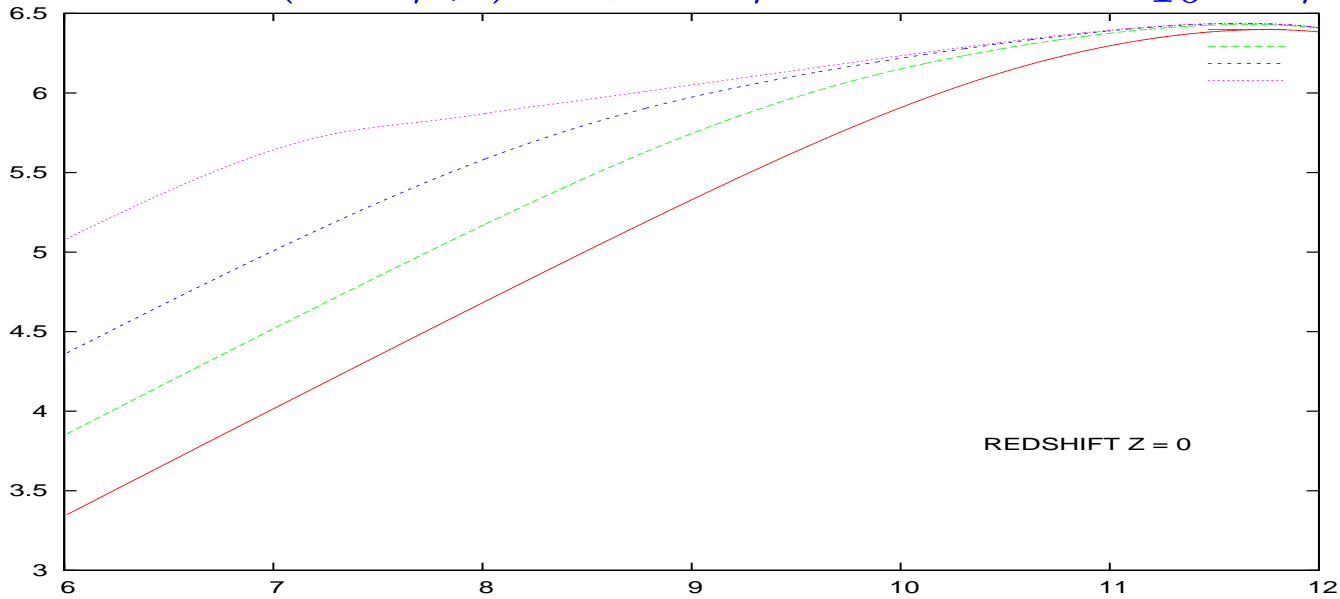


Box side = 22.6 Mpc. [C. Destri, private communication].

WDM.



# $(M^2/\rho) \log dN/dM$ vs. $\log_{10} M/M_\odot$



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



# 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, Ap J (2012). N. Amorisco, N. Evans, MNRAS (2012).

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

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

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

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

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

# The Phase-space density $Q(r)$

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

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

$I_2$  and  $I_4$  are momenta of the DM distribution function.

$g$  : # of internal degrees of freedom of the DM particle,  
 $1 \leq g \leq 4$ .

During structure formation  $Q$  **decreases** by a factor that we call  $Z$ , ( $Z > 1$ ) :

$$Q_{today} = \frac{1}{Z} Q_{prim}$$

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

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  $Q_{today} \sim (0.18 \text{ keV})^4$  Gilmore et al. 07/08.

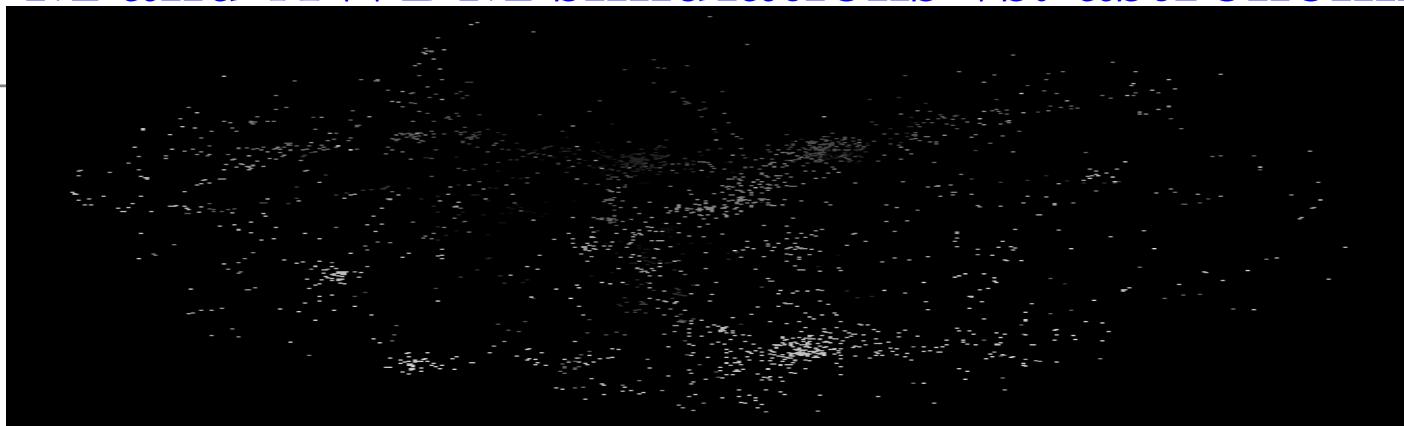
The spherical model gives  $Z \simeq 41000$  and  $N$ -body simulations indicate:  $10000 > Z > 1$ .  $Z$  is **galaxy dependent**.

As a consequence  $m$  is in the **keV scale**:  $1\text{keV} \lesssim m \lesssim 10\text{keV}$ .  
H. J. de Vega, N. G. Sanchez, MNRAS (2010)

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

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

# $\Lambda$ CDM and $\Lambda$ WDM simulations vs. astronomical observations



$\Lambda$ CDM



observations



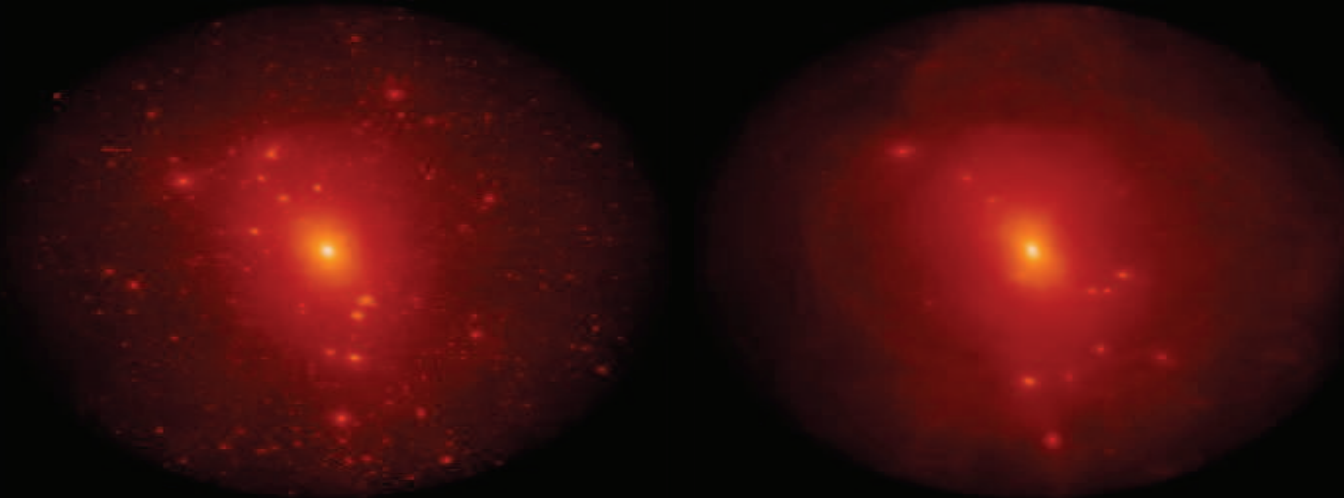
1keV WDM

# N-body WDM Simulations



cold dark matter

warm dark matter



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

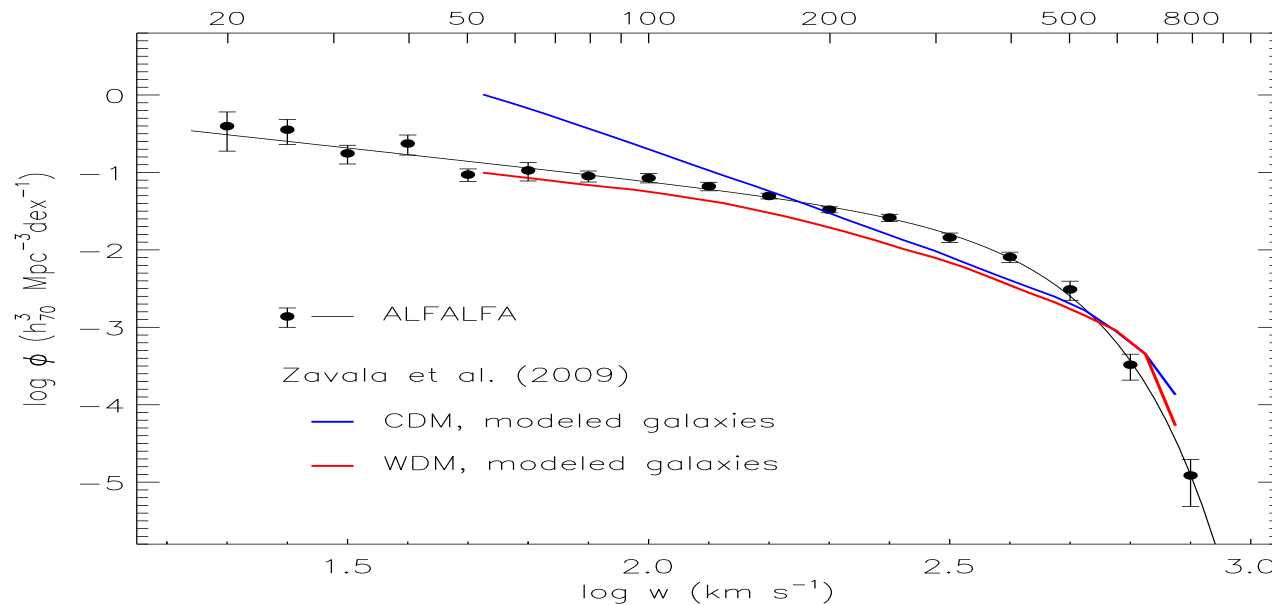
Wednesday, 15 June 2011

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).

# Velocity widths in galaxies



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.

# Quantum Bounds on Fermionic Dark Matter

The Pauli principle gives the **upper bound** to the phase space distribution function of spin- $\frac{1}{2}$  particles of mass  $m$ :

$$f(\vec{r}, \vec{p}) \leq 2$$

The DM mass density is given by:

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

where:

$\bar{f}(\vec{r})$  is the  $\vec{p}$ -average of  $f(\vec{r}, \vec{p})$  over a volume  $m^3 \sigma^3(\vec{r})$ ,

$\sigma(\vec{r})$  is the DM velocity dispersion,  $\sigma^2(\vec{r}) \equiv \langle v^2(\vec{r}) \rangle / 3$

$K \sim 1$  a pure number.

The Pauli bound  $\bar{f}(\vec{r}) \leq 2$  yields:  $Q(\vec{r}) \equiv \frac{\rho(\vec{r})}{\sigma^3(\vec{r})} \leq K \frac{m^4}{\hbar^3}$

This is an **absolute quantum upper bound** on  $Q(\vec{r})$  due to **quantum** physics, namely the Pauli principle.

$Q(\vec{r})$  can never take values larger than  $K m^4 / \hbar^3$ .

In the classical limit  $\hbar \rightarrow 0$  and the bound disappears.

# Classical physics breaks down near the galaxy center

$N$ -body simulations point to cuspy phase-space densities

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

$Q(r)$  derived within classical physics tends to infinity for  $r \rightarrow 0$  **violating** the Pauli principle bound.

Classical physics **breaks down** near the galaxy center.

The quantum upper bound on  $Q(r)$  is valid for

$$r \geq r_q \equiv \frac{\hbar^{\frac{3}{2}}}{m^2} \sqrt{\frac{Q_s}{K}} r_s, \quad (\text{setting } \beta = 2).$$

Observations yield:  $30 < \frac{r_s}{\text{pc}} < 5 \cdot 10^4$ ,  $2 \cdot 10^{-5} < \frac{\hbar^{\frac{3}{2}} \sqrt{Q_s}}{(\text{keV})^2} < 0.6$

Extreme values for spirals and ultra compact dwarfs.

Classical physics **breaks down** for  $r < r_q$  where  $r_q$  is in the parsec range for WDM  $m \sim \text{keV}$ .

The core radius must 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



# Dwarf galaxies as quantum objects

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

$d =$  Average distance between particles

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

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

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

The **larger**  $\mathcal{R}$  is for ultracompact dwarfs.

The **smaller**  $\mathcal{R}$  is for big spirals.

The ratio  $\mathcal{R}$  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 the fermionic 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.

# WDM properties

WDM is characterized by

- its initial power spectrum cutted off for scales below  $\sim 50$  kpc. Thus, structures are not formed in WDM for scales below  $\sim 50$  kpc.
- its initial velocity dispersion. However, this is negligible for  $z < 100$  where the non-linear regime starts (see Valageas, 2012).
- 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**.

So far, **not a single** objection arised against WDM.

# Quantum pressure vs. gravitational pressure

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

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

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

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

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

$$\begin{aligned} \text{Equilibrium: } P_q = P_G &\implies M_q = \frac{9}{2 \sqrt{\pi} m^2} \left( \frac{\hbar v}{G} \right)^{\frac{3}{2}} = \\ &= 0.797 \dots 10^6 M_{\odot} \left( \frac{\text{keV}}{m} \right)^2 \left( \frac{v}{10 \frac{\text{km}}{\text{s}}} \right)^{\frac{3}{2}} \end{aligned}$$

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

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

# Self-gravitating Fermions in the Thomas-Fermi approach

WDM is non-relativistic in the MD era.

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

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

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

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

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

**Thomas-Fermi eqs.** determine the chemical potential  $\mu(r)$

Boundary condition at

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

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

# Self-gravitating Fermions in the Thomas-Fermi approach

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  $\sim 10$  km/s, **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.

# Sterile Neutrinos in the SM of particle physics

SM symmetry group:  $SU(3)_{color} \otimes SU(2)_{weak} \otimes U(1)_{hypercharge}^{weak}$

Leptons are color singlets and **doublets** under weak SU(2).

Sterile neutrinos  $\nu_R$  do not participate to weak interactions.

Hence, they must be **singlets** of color, weak SU(2) and weak hypercharge.

The SM Higgs  $\Phi$  is a SU(2) doublet with a **nonzero** vacuum expectation value  $\Phi_0$ . It can couple Yukawa-type with the left and right handed leptons:

$$L_{Yuk} = y \bar{\nu}_L \nu_R \Phi_0 + h.c. \quad ,$$

$$y = \text{Yukawa coupling}, \quad \Phi_0 = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad , \quad v = 174 \text{ GeV.}$$

This induces a mixing (bilinear) term between  $\nu_L$  and  $\nu_R$  which produces **transmutations** of  $\nu_L \Leftrightarrow \nu_R$ .

# Sterile Neutrinos Mixing

Mixing and oscillations of particle states are typical of low energy particle physics !

- Flavor mixing: e- $\mu$  neutrino oscillations (explain solar neutrinos).
- $K^0 - \bar{K}^0$ ,  $B^0 - \bar{B}^0$  and  $D^0 - \bar{D}^0$  meson oscillations in connection with CP-violation.

Neutrino mass matrix:  $(\bar{\nu}_L \ \bar{\nu}_R) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$

$M =$  right-neutrino mass,  $m_D = y v$ ,  $M \gg m_D$ . Seesaw.

Mass eigenvalues:  $\frac{m_D^2}{M}$  and  $M$ , with eigenvectors:

- active neutrino:  $\nu_{active} \simeq \nu_L - \frac{m_D}{M} \nu_R$ .
- sterile neutrino:  $\nu_{sterile} \simeq \nu_R + \frac{m_D}{M} \nu_L$ ,  $M \gg m_D^2/M$ .



# Sterile Neutrinos

Choosing  $M \sim 1$  keV and  $m_D \sim 0.1$  eV is **consistent** with observations.

Mixing angle:  $\theta \sim \frac{m_D}{M} \sim 10^{-4}$  is appropriate **to produce enough** sterile neutrinos accounting for the observed DM.

Smallness of  $\theta$  makes sterile neutrinos difficult to detect.

Precise measure of nucleus recoil in tritium beta decay:  
 ${}^3H_1 \implies {}^3He_2 + e^- + \bar{\nu}$  can show the presence of a sterile **instead** of the active  $\bar{\nu}$  in the decay products.

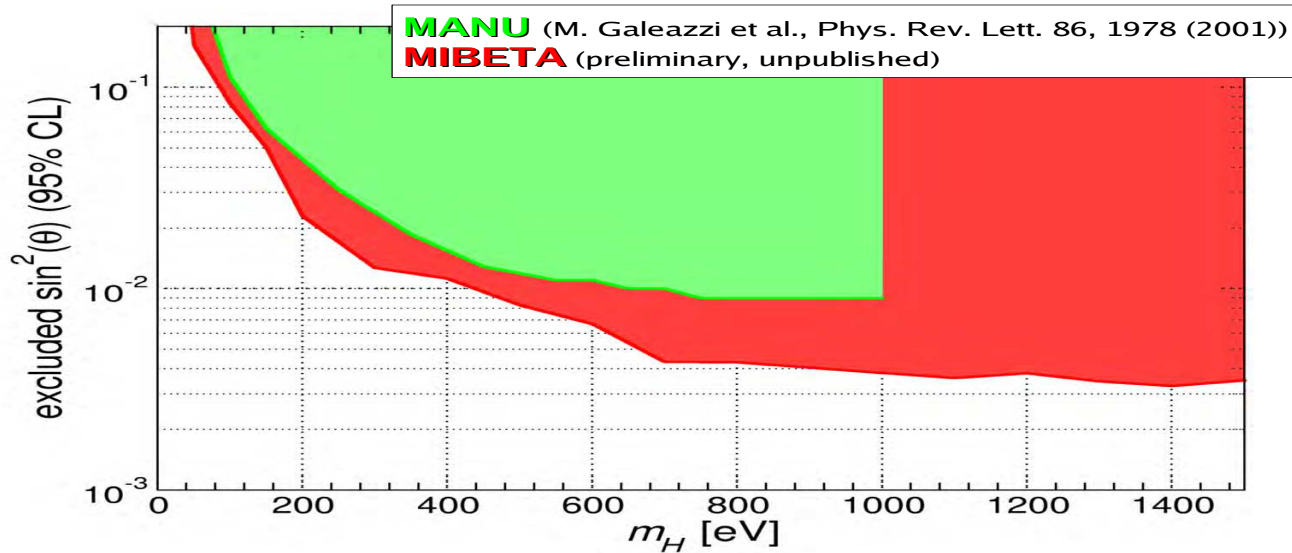
Rhenium 187 beta decay gives  $\theta < 0.095$  for 1 keV steriles [Galeazzi et al. PRL, 86, 1978 (2001)].

Available energy:  $Q({}^{187}Re) = 2.47$  keV,  $Q({}^3H_1) = 18.6$  keV.

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.

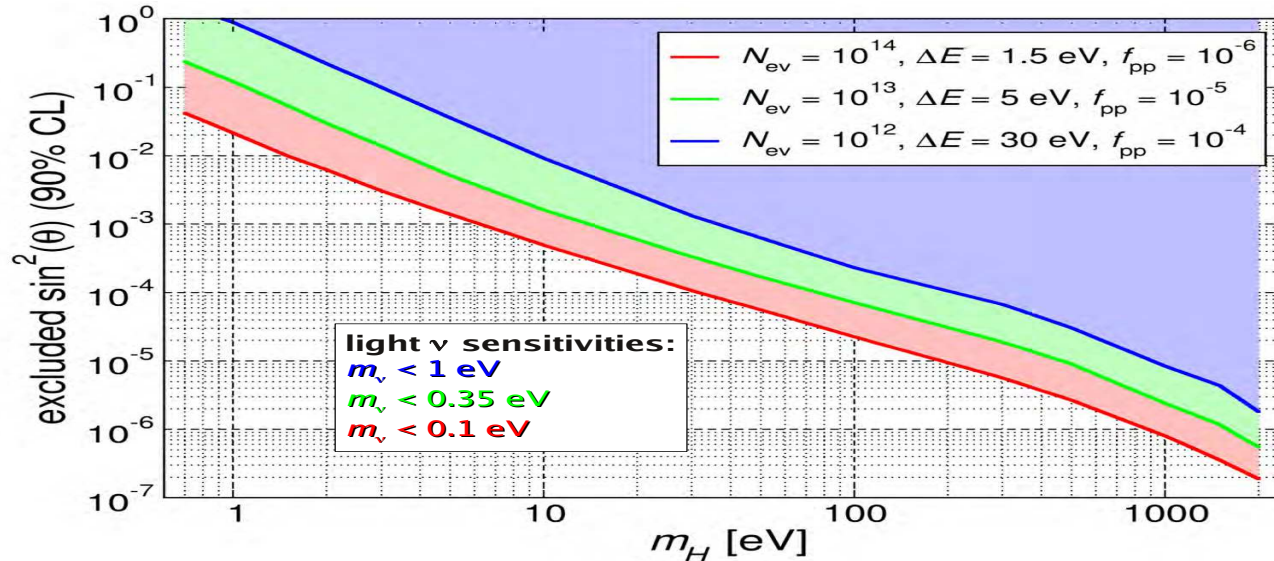
# MARE searches sterile neutrinos in beta decay

## Heavy neutrinos limits from past $^{187}\text{Re}$ experiments / 2



A. Nucciotti, Meudon Workshop 2011, 8-10 JUNE 2011 35

## MARE sensitivity to heavy neutrinos: $^{187}\text{Re}$ option



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

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

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

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

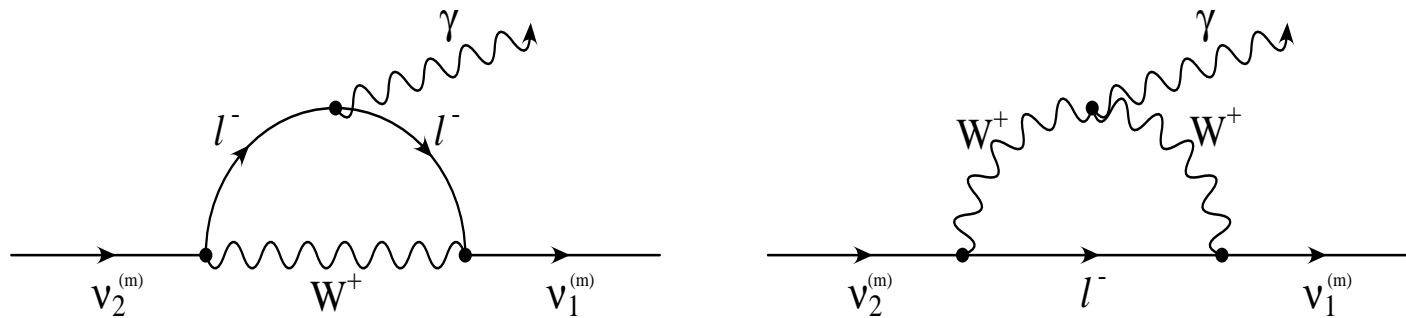
# X-ray detection of DM sterile neutrinos

Sterile neutrinos  $\nu_s$  decay into active neutrinos  $\nu_a$  plus **photons** ( $\gamma$ ) with a width:

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

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

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



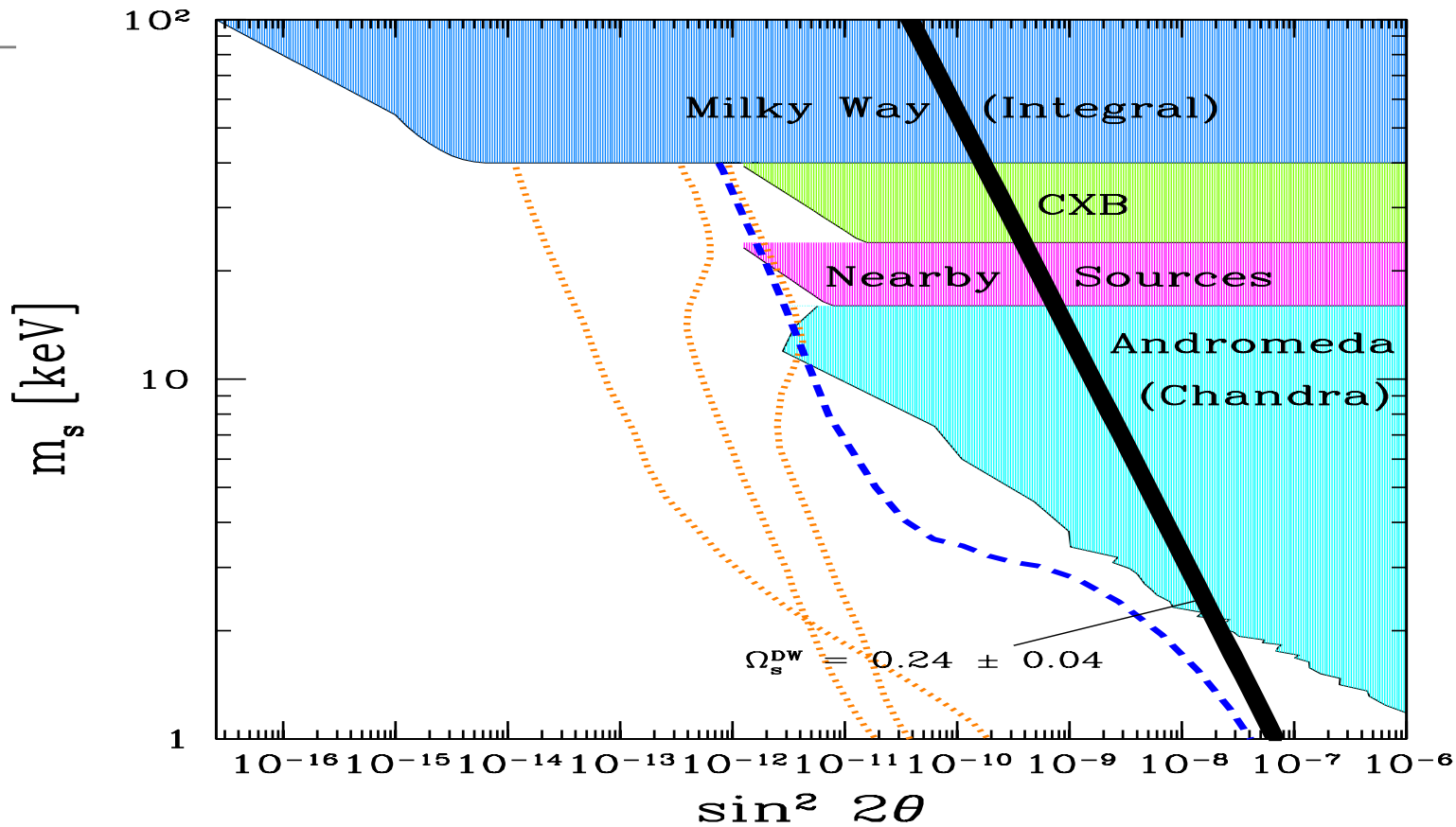
These X-rays **may be seen** in the sky looking to galaxies !

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

Future observations: DM bridge between M81 and M82  
 $\sim 50$  kpc. Overlap of DM halos.

satellite projects: IXO (killed) and Xenia (NASA).

# 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.

# Further Experiments to detect Sterile Neutrinos

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

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

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

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

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

## Summary: keV scale DM particles

- **Reproduce** the phase-space density observed in dwarf spheroidal and spiral galaxies (dV S, MNRAS 2010).
- Fermionic WDM provide **cored** galaxy profiles through **quantum effects** in agreement with observations (Destri, de Vega, Sanchez, 2012).
- The galaxy surface density  $\mu_0 \equiv \rho_0 r_0$  is **universal** up to  $\pm 10\%$  according to the observations. Its value  $\mu_0 \simeq (18 \text{ MeV})^3$  is reproduced by WDM (dV S S, New Astronomy, 2012). CDM simulations give 1000 times the observed value of  $\mu_0$  (Hoffman et al. ApJ 2007). Density profile scales and decreases for intermediate scales with the **spectral index**  $n_s$  :  $\rho(r) \sim r^{-1-n_s/2}$
- **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).

## 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. PRL (2009), P. Blasi, P. D. Serpico PRL (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
- Combining theoretical evolution of fluctuations through the Boltzmann-Vlasov equation with galaxy data points to a DM particle mass 3 - 10 keV. The keV mass scale holds independently of the DM particle physics model.
- 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.

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

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

Can DM inside the Sun help to explain the discrepancy?

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

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

Sterile neutrinos ? Other particle in the keV mass scale?

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

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

Quantum dynamical evolution to compute WDM cores.

Bounds from MARE on sterile neutrino mass and  $\theta$ .

Could KATRIN join the search of sterile neutrinos?

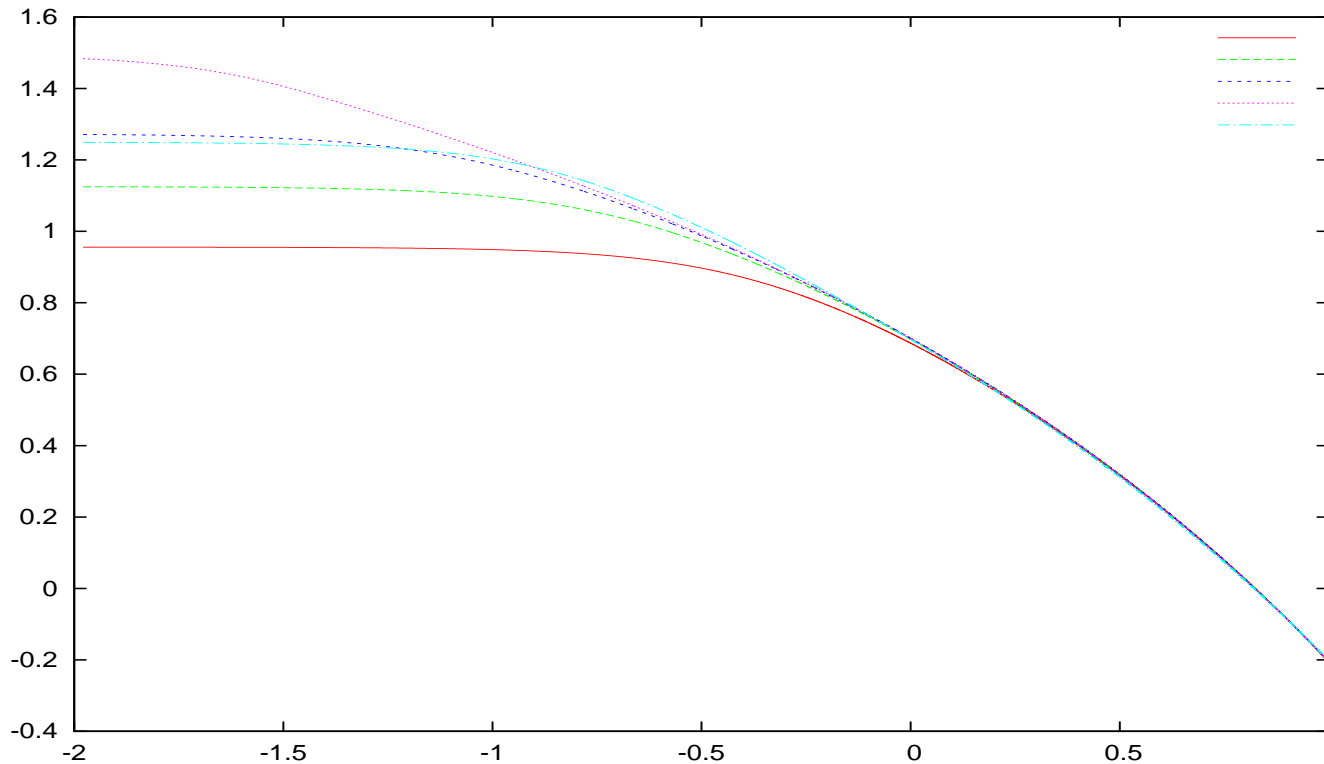
The Universe is our ultimate physics laboratory

THANK YOU VERY MUCH  
FOR YOUR ATTENTION!!

# The expected overdensity

The expected overdensity within a radius  $R$  in the linear regime

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



$\log \sigma(R)$  vs.  $\log(R/h \text{ Mpc})$  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.

# The Mass Function

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

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

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

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

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

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

# 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 wavenumber:

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

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

# Relics decoupling non-relativistic

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

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

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

$\sigma_0$ : thermally averaged total annihilation cross-section times the velocity.

From our previous **general equations** for  $m$  and  $g_d$ :

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

$$\text{Finally:} \quad \sqrt{m T_d} = 1.47 \left(\frac{Z}{g_d}\right)^{\frac{1}{3}} \text{ keV}$$

We used  $\rho_{DM}$  today **and** the decrease of the phase space density by a factor  $Z$ .

## 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

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

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

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

**Only** using  $\rho_{DM}$  today (**ignoring** the phase space density information) gives **one** equation with **three** unknowns:

$m$ ,  $T_d$  and  $\sigma_0$ ,

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

WIMPS with  $m = 100 \text{ GeV}$  and  $T_d = 5 \text{ GeV}$  require  $Z \sim 10^{23}$ .

# Universe Inventory

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

Dark Energy ( $\Lambda$ ): 74 % , Dark Matter: 21 %

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

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

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

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

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

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



# 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 !