The History of the Universe

It is a history of EXPANSION and cooling down.

EXPANSION: the space itself expands with the time. All lengths grow as time goes on: wavelengths, distances between objects. Atoms and elementary particle sizes remain unchanged.

Cooling: temperature decreases as lenghts increase.

The expansion of the Universe started explosively fast: the Big Bang !! The Big Bang has no center. The Universe expands similarly at all space points. Homogeneous and isotropic expansion at all times.

This is very different to supernova explosions, atomic bombs or firecrackers.

Universe homogeneous and isotropic during 80 Myr. Since then, structures (galaxies) form via dynamical gravitational processes.

Inflation and subsequent eras of the Universe

Main Events since the Big Bang	Time from beginning	Tempe-rature	Expansion since B B
Inflation - DED	10^{-36} sec	10^{29} K	10^{28}
Protons & neutrons form - RD	10^{-5} sec	10^{12} K	10^{45}
D, He, Li form - RD	20 sec	10^{9} K	10^{48}
Non-relativistic ($v \ll c$) particles dominate - MD	57000 yr	8000 K	3×10^{53}
Atoms and CMB form	370000 yr	3000 K	10^{54}
Galaxies and Stars start to form - MD	80 Myr	90 K	10^{55}
Today - DED	13.7 Gyr	3 K	10^{57}

DED: DE dominated, RD: radiation dom, MD, matter dom.

Standard Cosmological Model:
Ordinary Matter + Dark Matter + Cosmological Constant

- Begins by the inflationary era.
- Gravity is described by Einstein's General Relativity. Matter determines the spacetime geometry.
- Ordinary Matter described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model. Strong, electromagnetic and weak interactions involving quarks, gluons, protons, electrons, photons and neutrinos.
- Dark matter plays a crucial role in galaxy and structures formation. DM could be a sterile neutrino which does not interact through the SM and has mass $\sim$ keV.
- Dark energy uniformly distributed in space. Repulsive gravitational force. Described by the cosmological constant Λ.

The Universe Today is Essentially Empty

Inter galactic distances $\sim$ Mpc. (pc = 3.0857×10^{13} kms.)

Galaxy sizes $\sim 0.0001 - 0.1$ Mpc. (pc = 3.262 light years.)

99.9 % of the universe volume is the intergalactic space with an average energy density of 5 proton masses per m^3 (cosmological constant).

Galaxy masses: $10^6 - 10^{12}\ M_\odot$ from dwarf compact galaxies to (diluted) big galaxies spirals.

Galaxy density:
$\sim 4000 - 40000$ proton masses per m^3 for big galaxies.

$\sim 4 \times 10^6$ proton masses per m^3 for small compact galaxies.

For comparison: air density at the atmospheric pressure and 0^o C $\sim 3.9 \times 10^{26}$ proton masses per m^3.

The Fossil Cosmic Microwave bkg and Primordial Gravitons

Cosmic microwave background almost homogeneous and isotropic plus small inhomogeneities $\sim 10^{-4}$.

Inflation is the only explanation for the CMB including these small fluctuations of quantum origin $\sim 10^{-4}$.

Density CMB anisotropies first detected in 1992 by COBE.

Einstein's General Relativity predicts the existence of gravitational waves. Oscillations of the space-time itself.

Primordial gravitons are produced during inflation. They appear as tensor fluctuations in the CMB anisotropies.

Primordial gravitons first detected in the CMB by BICEP in March 2014. Detected ratio r of gravitons to density fluctuations $r \sim 0.15 - 0.20$

This detection show two important results: a) the existence of gravitational waves, b) their existence as quantized gravitons.

Effective Theory of Inflation (ETI) confirmed by Planck

Quantity	ETI Prediction	Planck 2013
Spectral index $1 - n_s$	order $1/N = 0.02$	0.04
Running $dn_s/dlnk$	order $1/N^2 = 0.0004$	< 0.01
Non-Gaussianity f_{NL}	order $1/N = 0.02$	< 6
	ETI + WMAP+LSS	
tensor/scalar ratio r	r > 0.02	< 0.11 see BICE
inflaton potential curvature $V''(0)$	$V''(0) < 0$	$V''(0) < 0$

ETI + WMAP+LSS means the MCMC analysis combining the ETI with WMAP and LSS data. Such analysis calls for an inflaton potential with negative curvature at horizon exit. The double well potential is favoured (new inflation).
D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:0901.0549, IJMPA 24, 3669-3864 (2009).

Recent News on Cosmological Observables

Before 2013: Hubble constant $H_0 = 73.8 \pm 2.4 \, \frac{\text{km}}{\text{s}} \, \frac{1}{\text{Mpc}}$ from direct observations of Cepheids by HST, $\Omega_m = 0.27 \pm 0.03$. A G Riess et al. ApJ 730, 119 (2011).

Planck 2013: $H_0 = 67.3 \pm 1.2 \, \frac{\text{km}}{\text{s}} \, \frac{1}{\text{Mpc}}$. $\Omega_m = 0.32 \pm 0.02$.

Planck assumed here only three massless neutrinos and no sterile neutrinos ν_s.

There is today strong evidence for ν_s with $m_s \sim$ eV from short baseline experiments (reactors, MiniBoone, LSND).

Adding one ν_s yields:
$H_0 = 70 \pm 1.2 \, \frac{\text{km}}{\text{s}} \, \frac{1}{\text{Mpc}}$. $\Omega_m = 0.30 \pm 0.01$ for $m_s = 0.4$ eV.

These values for H_0 and Ω_m are compatible with the direct astronomical measurements.

M. Wyman et al. PRL. 112, 051302 (2014), J. Hamann & J. Haserkamp, JCAP,10,044H (2013) R. Battye & A. Moss, PRL. 112. 051303 (2014), S. Gariazzo et al. JHEP 1311 (2013) 211

Active and Sterile Neutrinos

Active neutrinos (e, muon and tau) participate of weak interactions. Sterile neutrinos do not.

Neutrinos are characterized by their masses and mixing angles. Neutrinos can transform into each other.

Masses and mixing angles are obtained from nuclear (reactor) and particle physics experiments.
So far no theory for them.

WMAP9 and Planck gave $r < 0.11$ in tension with BICEP.

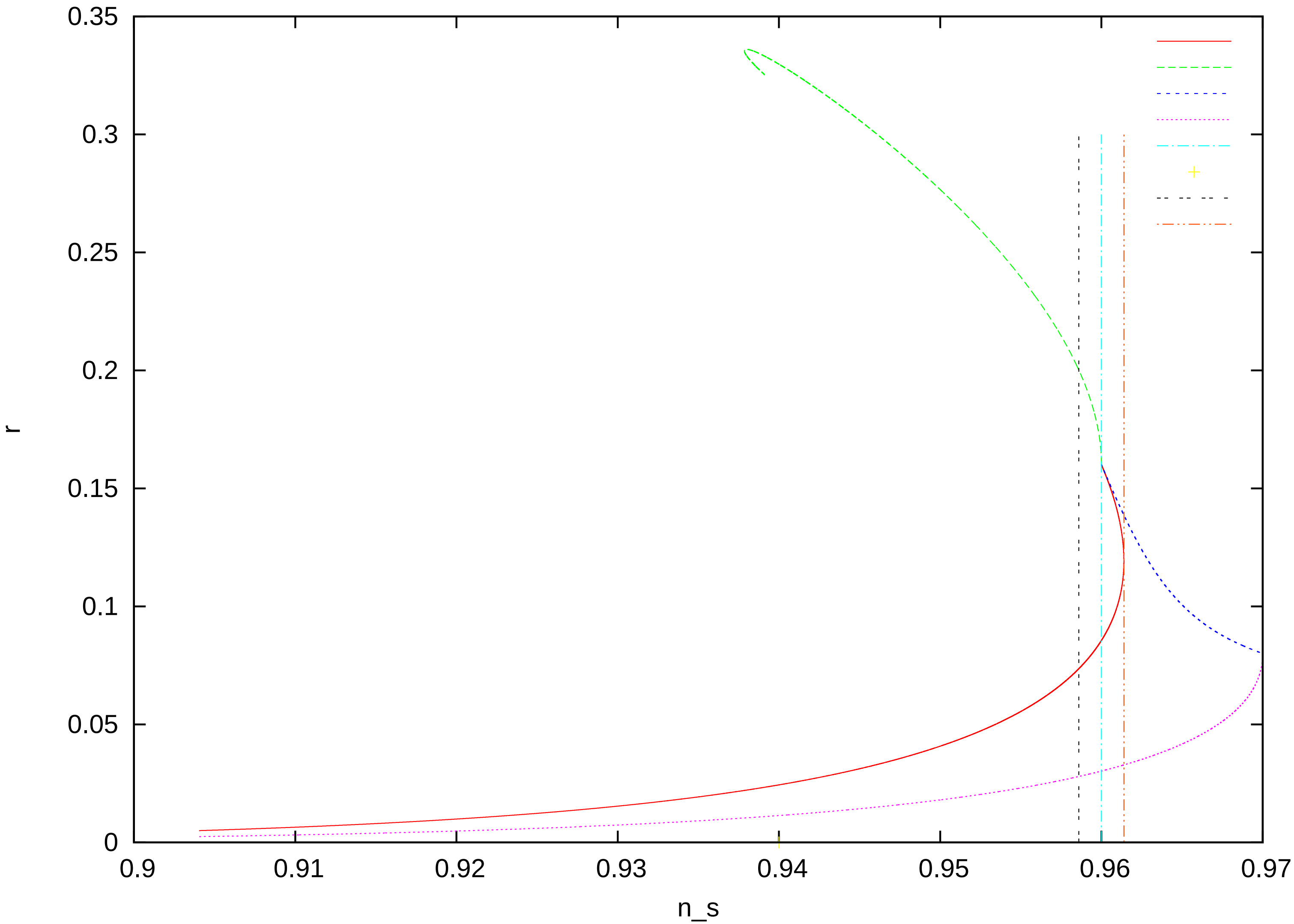
An extra sterile species is able to reconcile WMAP9 and Planck data with H_0 supernova data and the BICEP r.

Resulting sterile neutrino mass: $m_s \simeq 0.45$ eV

C. Dvorkin et al. arXiv:1403.8049, M. Archidiacono et al. arXiv:1404.1794, J. F. Zhang et al. 1403.7028.

Planck data analysis is faulty due to inadequate priors: zero active neutrino masses and no steriles.

Single and Double Well Inflaton Potentials



The cosmic banana for double well potentials (N=50) (de Vega, Sanchez, PRD 2006). Data 2014: $n_s = 0.96 \pm 0.014$.

How the Universe took its present aspect?

The Universe was homogeneous and isotropic after inflation thanks to the fast and gigantic expansion stretching lenghts by a factor $e^{64} \simeq 10^{28}$.

The universe by the end of inflation is a extraordinarily hot plasma at $T \sim 10^{14}$ GeV $\sim 10^{27}$ K.

However, small ($\sim 10^{-5}$) quantum fluctuations were of course present.

These inflationary quantum fluctuations are the seeds of

- the structure formation in the universe: galaxies, clusters, stars, planets (and all on them), ...
- the CMB anisotropies today.

That is, our present universe (including ourselves) was built out of inflationary quantum fluctuations.

Universe Inventory Today

The universe is spatially flat.
Curvature is present in the space-time geometry.

Today: Dark Energy (Λ): 73 % , Dark Matter: 22 %

Baryons $+$ electrons: 4.5 % , Radiation ($\gamma + \nu$): 0.0085%

83 % of the matter in the Universe is DARK.

Total average energy density today (very dilute!):

$\rho(\text{today}) = 0.947\ 10^{-29}\ \frac{\text{g}}{\text{cm}^3} \simeq$ 5 proton masses per m^3

DM dominates in the halos of galaxies (external part).
Ordinary matter dominates around the center of galaxies.

Most galaxies exhibit a gigantic black hole in the center.
Central black hole mass ~ 0.001 galaxy mass.

Galaxies form out of matter collapse via gravitational dynamics.

What is the nature of the Dark Matter?

83% of the matter in the universe is Dark.

Only the DM gravitational effects are noticed and they are necessary to explain the present structure of the Universe.

DM (dark matter) particles are neutral and so weakly interacting that no effects are so far detectable.

Theoretical analysis combined with astrophysical data from galaxy observations as:

- Observed galaxy densities and velocity dispersions.
- Observed galaxy density profiles are cored.
- Acceleration of gravity in the surface of DM dominated galaxies is universal $g \simeq 1.7 \times 10^{-11} \, m/s^2 \; = 540 \text{ kpc}/(\text{Gyr})^2$.

points towards a DM particle mass in the keV scale called warm dark matter (WDM). 2 keV = 1/250 electron mass.

How to detect sterile neutrinos?

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

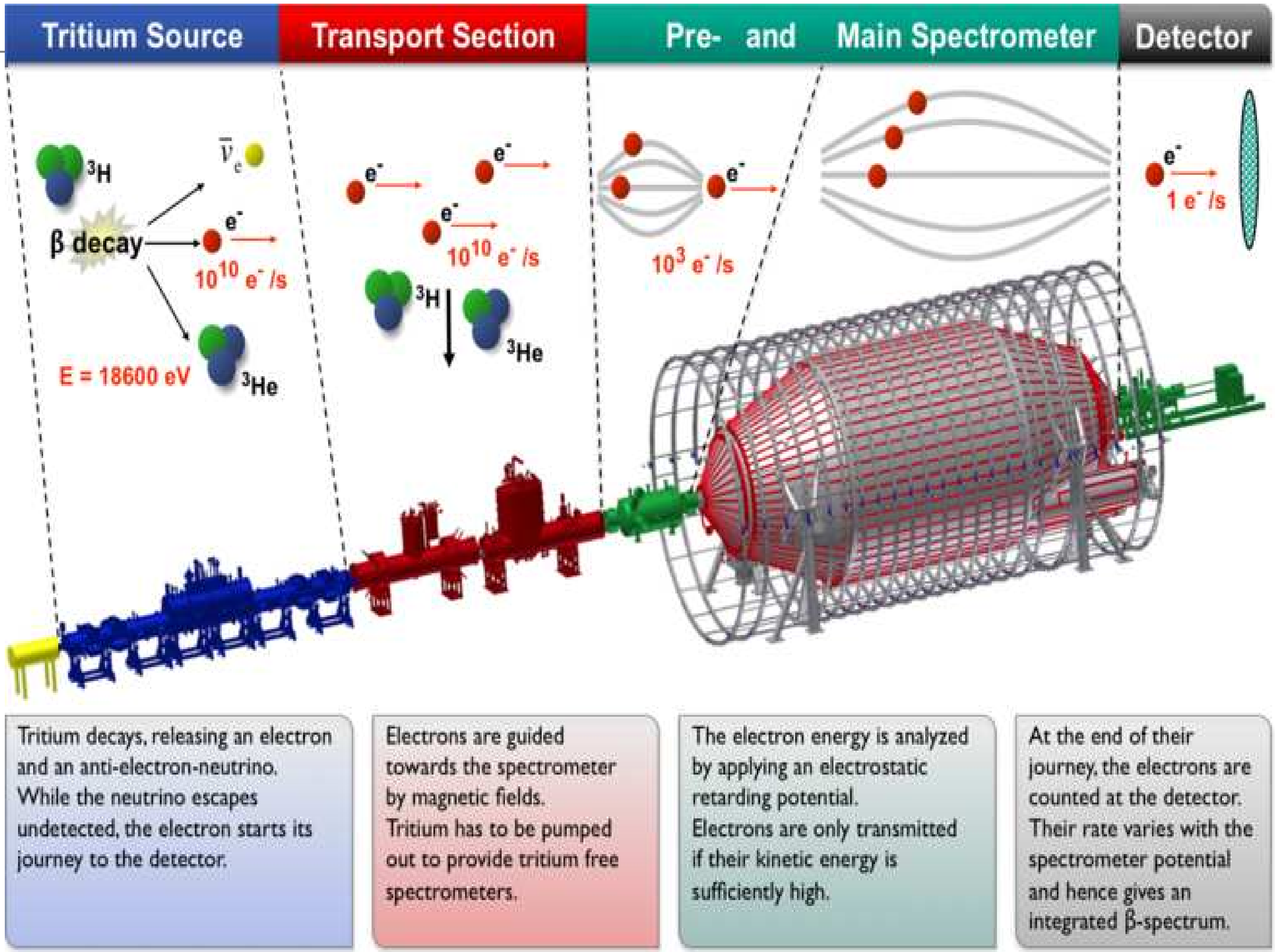
The nonradiative de-excitation of the Dy^* is observed and is different for ν_s in the keV range than for active ν_e.

Experiments that may detect sterile neutrinos:

MARE (Milano), KATRIN (Karlsruhe), PTOLEMY (Princeton), ECHo (Heidelberg), HOLMES (Grand Sasso).

They search the mass of the ordinary neutrino.

The Katrin Experiment



Quantum physics in Galaxies

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

$v =$mean velocity, $m =$ DM particle mass. $\rho =$ mass density.

$d =$ mean distance between particles $= \left(\frac{m}{\rho}\right)^{\frac{1}{3}}$

When $\lambda_{dB} \ll d, \quad \Longrightarrow \quad$ classical system,

when $\lambda_{dB} \sim d$ or $\lambda_{dB} > d \quad \Longrightarrow \quad$ quantum system.

Observed values in Galaxies:

$$2 \times 10^{-3} \left(\frac{\mathrm{keV}}{m}\right)^{\frac{4}{3}} < \frac{\lambda_{dB}}{d} < 1.4 \left(\frac{\mathrm{keV}}{m}\right)^{\frac{4}{3}}$$

The larger ratio is for compact dwarfs $\Rightarrow$ quantum object.

The smaller ratio is for big spirals.

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

The Universe is our ultimate physics laboratory !!

THANK YOU VERY MUCH

FOR YOUR ATTENTION!!

Standard Cosmological Model: ΛWDM

ΛCDM = Warm 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 measured from Supernovas
- Gravitational Lensing Observations
- Lyman α Forest Observations
- Hubble Constant (H_0) Measurements
- Properties of Clusters of Galaxies
- Measurements of the Age of the Universe
- Galaxy structure only explained by WDM

Quantum pressure vs. gravitational pressure

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

momentum $= p \sim \hbar/\Delta x \sim \hbar\, n^{\frac{1}{3}}$, from Heisenberg principle

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 $m \sim$ keV the values of $M_q,\ R_q$ and v are consistent with the dwarf galaxy observations !! .

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