

L'UNIVERS: de son origine à nos jours

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DERNIERES NOUVELLES DE L'UNIVERS

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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 lengths 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**.

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

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 distribute in space. Described by the cosmological constant Λ .

The Fossil Cosmic Microwave bkg and Primordial Graviton

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** $\sim 10^{-4}$.

CMB fluctuations have **unique** information about the inflationary era, the **first** 10^{-36} sec of the Universe.

CMB anisotropies first detected in 1992 by COBE satellite.

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

The effective theory of inflation à la Ginsburg-Landau gives a **precise prediction** for the amount of primordial gravitons (r) produced during inflation: 4 to 5 % compared with the CMB temperature fluctuations.

Primordial gravitons **hard** to detect in the CMB anisotropies.

The Planck satellite **may** detect r (borderline !, 2014)

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 $dn_s/d\ln k$	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	$r = 0.04-0.05$	< 0.11
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).

How the Universe took its present aspect?

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

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

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!):

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

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

$$g \simeq 1.7 \times 10^{-11} \text{ m/s}^2 = 540 \text{ kpc}/(\text{Gyr})^2.$$

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

Quantum physics in Galaxies

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

v = mean velocity, m = DM particle mass. ρ = mass density.

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

When $\lambda_{dB} \ll d$, $\implies$ **classical** system,

when $\lambda_{dB} \sim d$ or $\lambda_{dB} > d \implies$ **quantum system**.

Observed values in Galaxies:

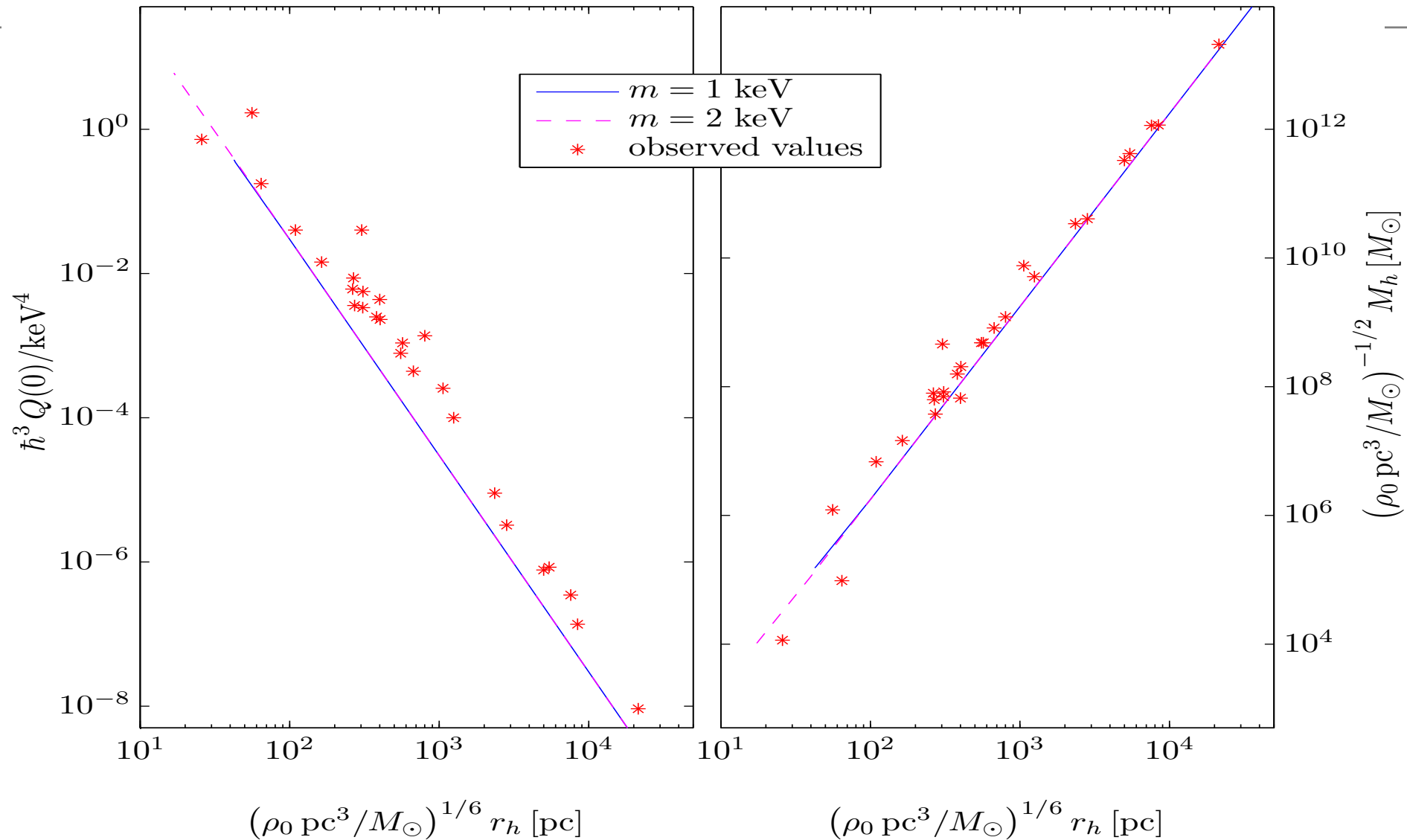
$$2 \times 10^{-3} \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}} < \frac{\lambda_{dB}}{d} < 1.4 \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}}$$

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

The **smaller** ratio is for big spirals.

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

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



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

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 $10^{-3} \text{ }^\circ\text{K} < E_0 < 10 \text{ }^\circ\text{K}$

colder = ultracompact, warmer = large spirals.

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

The Universe is our ultimate physics laboratory !!

THANK YOU VERY MUCH
FOR YOUR ATTENTION!!

Standard Cosmological Model: Λ WDM

Λ CDM = 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

Abell 1689 cluster



Dark Matter Map in Galaxy Cluster Abell 1689
Hubble Space Telescope ACS/WFC

NASA, ESA, and D. Coe (JPL/Caltech and STScI)

STScI-PRC10-37

Quantum pressure vs. gravitational pressure

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

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: $P_q = P_G \implies$

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

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

for $m \sim \text{keV}$ 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.