L'UNIVERS: de son origine à nos jours

H. J. de Vega

LPTHE, CNRS/Université P. & M. Curie (Paris VI)

DERNIERES NOUVELLES DE L'UNIVERS

15 Mars 2013 - Observatoire de Paris

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.
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	Tempe- rature	Expansion fact since beginnin
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 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 $\sim 10^{-4}$.
- 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)

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.
- surface acceleration of gravity in DM dominated galaxies.

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

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

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:

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

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

The smaller ratio is for big spirals.

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

Quantum pressure vs. gravitational pressure

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

momentum $= p \sim \hbar/\Delta x \sim \hbar\ n^{\frac13}$, from Heisenberg principle

particle number density $= n = \frac{M_q}{\frac43\ \pi\ R_q^3\ m}$

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: $P_q = P_G \Longrightarrow$

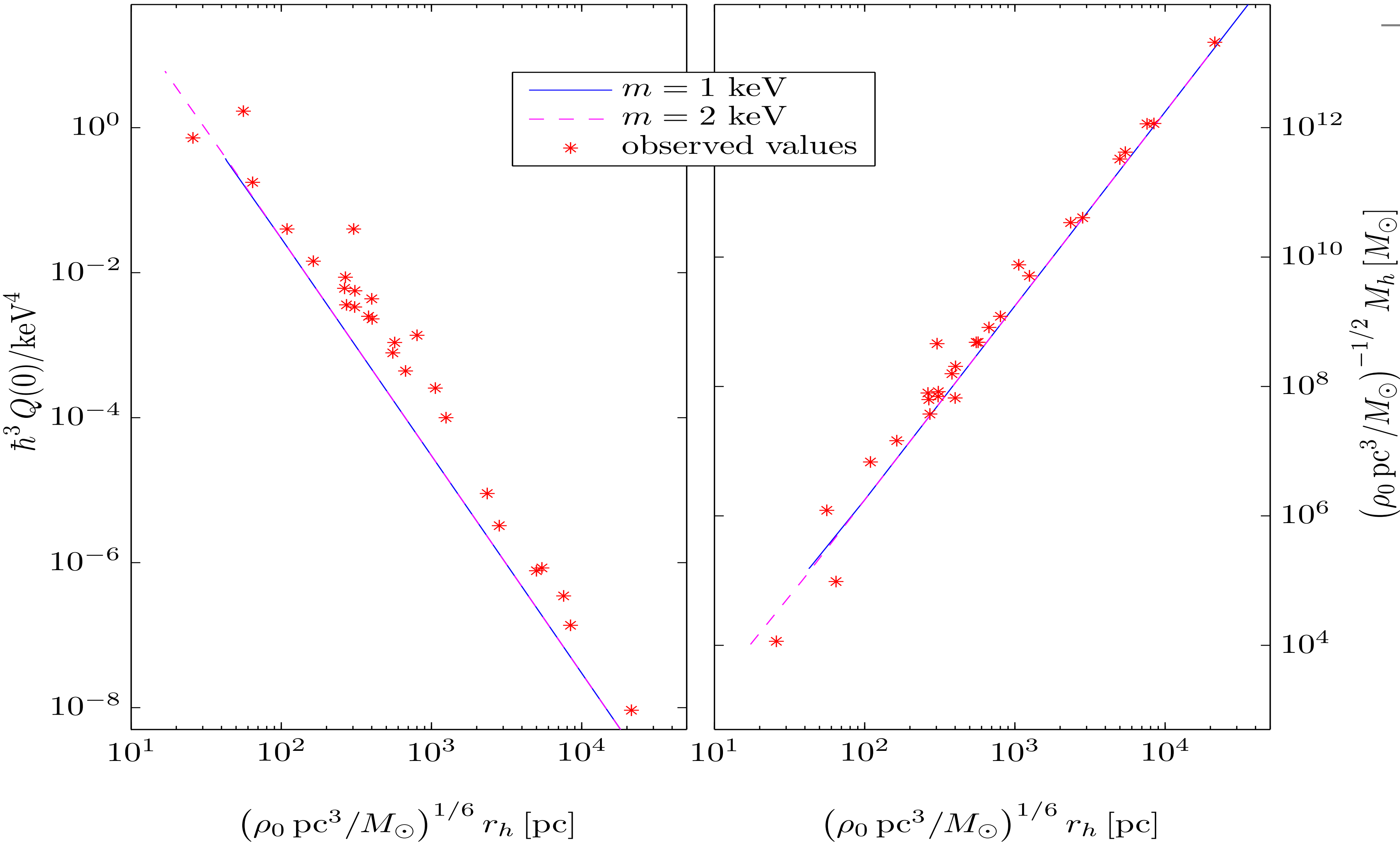
$$R_q = \frac{3^{\frac53}}{(4\ \pi)^{\frac23}}\ \frac{\hbar^2}{G\ m^{\frac83}\ M_q^{\frac13}} = 10.6\ldots \text{pc} \left(\frac{10^6\ M_\odot}{M_q}\right)^{\frac13} \ \left(\frac{\text{keV}}{m}\right)^{\frac83}$$

$$v = \left(\frac{4\,\pi}{81}\right)^{\frac13}\ \frac{G}{\hbar}\ m^{\frac43}\ M_q^{\frac23} = 11.6\ \frac{\text{km}}{\text{s}}\ \left(\frac{\text{keV}}{m}\right)^{\frac43}\ \left(\frac{M_q}{10^6\ M_\odot}\right)^{\frac23}$$

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.

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} ^{o}K $< E_0 <$ 10 ^{o}K

colder = ultracompact, warmer = large spirals.

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

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

Abell 1689 cluster