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lecture cource on

Astroparticle physics

15.09.2009 – 15.12.2009

7 Dark matter

7.1 Dark matter

Evidence for dark matter – 1 – Coma galaxy cluster

- At the beginning of 1930's F. Zwicky observed that galaxies in the Coma cluster were moving too fast in order to remain (by gravity) in the cluster
  - something else, that cannot be seen, must be holding the galaxies together in the cluster
- More evidence until 40 years later (Vera Rubin)
  - the gas and stars in the outer parts of galaxies were moving too fast with respect to the observed mass
    $\Longrightarrow$ rotation curve

7.1 Dark matter

Evidence for dark matter – 2 – rotation curves

- Rotation velocity measurements of star and galaxies as a function of distance
- Spiral galaxy has most of the luminous material concentrated in a central hub and a thin disk
- If only luminous material exist, then
  - for stars inside the hub $M(< r) \propto r^3$ and therefore $v \propto r$
  - for stars outside the hub $M \sim$ constant and $v \propto r^{-1/2}$

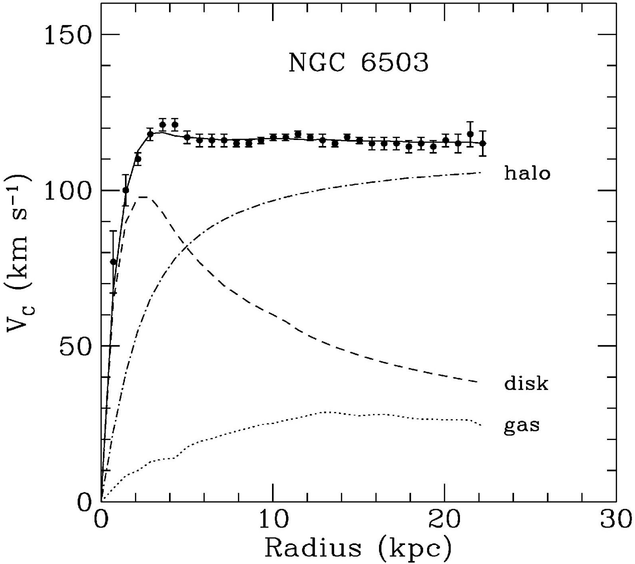
  $\Longrightarrow$ Velocity should increase at small distances and decrease at large distances

- It is observed, on the contrary, that the rotation curves are quite flat at large distances (halo)

  $\Longrightarrow$ the bulk of the galactic mass – typically 80–90% – would be in the form of dark (i.e. non-luminous) matter in the halo

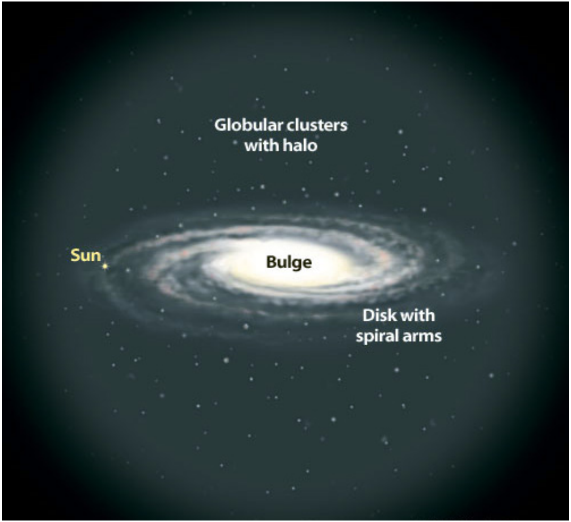
7.1 Dark matter

Evidence for dark matter – 2 – rotation curves of galaxy NGC6503



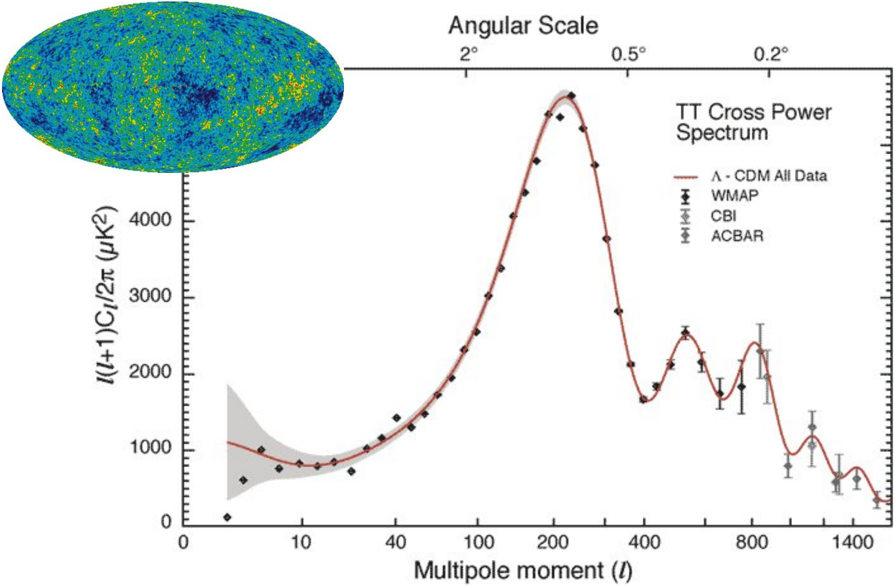
7.1 Dark matter

Evidence for dark matter – 2 – halo



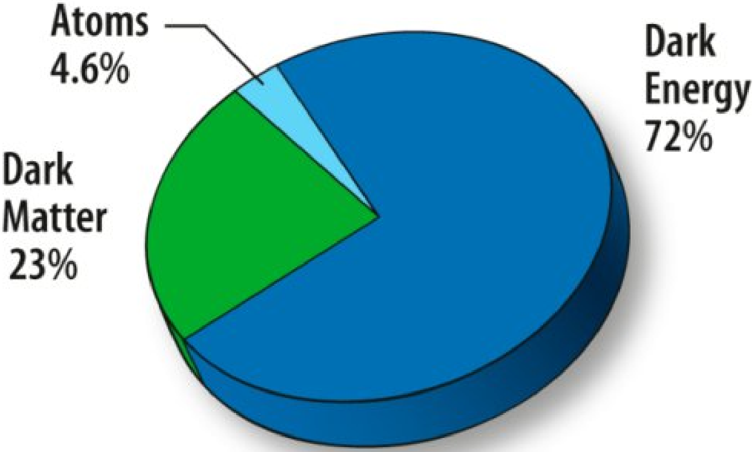
7.1 Dark matter

Evidence for dark matter – 3 – WMAP – 1



7.1 Dark matter

Evidence for dark matter – 3 – WMAP – 2



7.1 Dark matter

Evidence for dark matter – conclusion

- There is astrophysical and cosmological evidence that large quantities of dark matter must be hidden somewhere in the universe
  - the dynamics of galaxies and galactic clusters can only be understood if the dominating part of the gravitation is caused by non-luminous matter
- What can the non-luminous matter be?

7.2 Dark matter

Dark matter candidates – terminology

- Baryonic dark matter
- Non-baryonic dark matter

- Baryonic dark matter
  - ordinary matter consisting of protons and neutrons
  - all that can or cannot be seen: interstellar dust, giant planets, 'old' stars (white, red and brown dwarfs), black holes, ...
  - MACHOs – MAssive Compact Halo Objects
  - It is known to exist but **explains only a tiny portion of dark matter**

- Non-baryonic dark matter
  classified according to temperature in the early universe (decoupling)
  - cold dark matter
  - warm dark matter
  - hot dark matter

7.2 Dark matter

Dark matter candidates – non-baryonic dark matter

- Hot dark matter
  - relativistic particles
  - example candidate: neutrinos

  $\Longrightarrow$ known to exist, but are hot

  $\Longrightarrow$ masses not heavy enough and number not large enough to explain dark matter
- Warm dark matter
  - semi-relativistic particles
  - example candidates: keV-mass sterile neutrinos and gravitons

  $\Longrightarrow$ not known
- Cold dark matter
  - non-relativistic particles
  - example candidates: neutralinos, axions, WIMPZILLAs, solitons (B-balls and Q-balls), etc

  $\Longrightarrow$ the most popular hypothesis for dark matter: WIMPs (Weakly Interacting Massive Particles)

7.3 Dark matter

Supersymmetry – SUSY

- In supersymmetric theories each fermion (half-integer spin) is associated with a bosonic (integer spin) partner and each boson has a fermionic partner
  - squark, slepton, gluino, photino, zino, higgsino, neutralino, gravitino, ...
  - doubles the number of elementary particles
  - no SUSY particles have been found
- From accelerator experiments $\Longrightarrow$ masses higher than 100 GeV $(100 m_{\mathrm{p}})$,
- Massive SUSY particle would decay to lighter SUSY particles, and eventually to the lightest superparticle
  - the lightest SUSY particle (LSP) would be stable
- The LSP is the most favourite candidate for WIMPs
  - neutralino

7.4 Dark matter

Energy densities – critical density

- A quantitative measure for the composition of the universe can be given by the critical density (ρ_c)

$$\rho_c = \frac{3H_0^2}{8\pi G} \approx 1.88 \times 10^{-26} h^2 \text{ kg} \cdot \text{m}^{-3} \approx 10.5 \text{ h}^2 \text{ keV} \cdot \text{c}^{-2} \cdot \text{cm}^{-3},$$

  where H_0 is the present value of the Hubble constant, h being the dimensioless form of H_0 in units of 100 km$\cdot$s$^{-1}\cdot$Mpc^{-1} (the current xperimental value of h is $\sim$0.7), and G is the gravitation constant
- Any particular component is then given by

$$\Omega_x = \frac{\rho_x}{\rho_c}$$

7.4 Dark matter

Energy densities – conclusion

$\Omega_{\mathrm{TOT}} \approx 1$

- $\Omega_{\mathrm{MATTER}} \approx 0.3$
  - $\Omega_{\mathrm{BARY}} \approx 0.05$
    - $\Omega_{\mathrm{LUM}} \approx 0.005$
    - $\Omega_{\mathrm{DARK}} \approx 0.05$
  - $\Omega_{\mathrm{NONB}} \approx 0.25$
    - $\Omega_{\mathrm{HOT-DM}} \approx 0.005$
    - $\Omega_{\mathrm{COLD-DM}} \approx 0.25$
- $\Omega_{\mathrm{DARK-ENERGY}} \approx 0.7$

7.5 Dark matter

and Galaxy formation

- The question of galaxy formation is closely related with the problem of dark matter
- The models of galaxy formation depend very sensitively on whether the the universe is dominated by hot or cold dark matter
  - models assume galaxies have originated from (quantum) fluctuations which have developed to larger gravitational structures
  - two different scenarios can be distinguished: hot and cold dark matter

7.5 Dark matter

and Galaxy formation – hot dark matter

- Low-mass and relativistic neutrinos could easily escape from mass structures
- Fluctuations below a certain critical mass would have not grown to galaxies
  - for neutrinos of 20 eV a critical mass of $\sim 10^{16}$ M_{SUN} is required for the structure formation to set in
- "Top-down scenario"
  – first largest structures (superclusters), then clusters and galaxies latest
  - allows only small z values ($z \leq 1$), but Hubble observations show that large galaxies exist for $z \geq 3$
  - This is one argument to exclude neutrinos as main dark matter component

7.5 Dark matter

and Galaxy formation – cold dark matter

- Massive, weakly interacting and mostly non-relativistic particles will be gravitationally bound already to mass fluctuations of smaller sizes
- If cold dark matter dominate, the models show that initially small mass structures collapse and can grow by further mass attractions to form galaxies
- "Bottom-up scenario"
  – the galaxies would then develop to galactic clusters and later superclusters
  - cold dark matter then favours a scenario in which smaller structures would be formed first and then develop into larger structures
  - confirmed by observations of, for example, COBE and WMAP satellites

7.6 Dark matter

Dark matter experiments – WIMPs

- Direct or indirect experiments
- Direct experiments for dark matter
  - scattering of a WIMP inside the detector material is observed
  - results in a low-energy recoil nucleus
  - WIMP rate may be expected to exhibit time dependence
- Indirect experiments for dark matter
  - detection of the annihilation products of WIMPs (high-energy neutrinos)
  - gravitational trapping of WIMPs at the core of the Sun or the Earth
  - large-volume Cherenkov detector etc

7.6 Dark matter

Dark matter experiments – WIMPs – direct experiments – 1

- The WIMP velocities are expected to be of the order of galactic excape velocities, $v_\chi \sim 10^{-3}c$ (non-relativistic)
- With $m_\chi \sim 100$ GeV the maximum energy of the recoil nucleus (of A ∼50) of the detector is $E_{\mathrm{r,max}}$ ∼50 keV
  - uniform distribution between 0 and $E_{\mathrm{r,max}}$
  - very low-energy recoil $\Longrightarrow$ difficult to observe

- Event rates in a detector varies depending whether the cross section is spin-dependent (incoherent) of coherent
  - $R \sim 1$ event $\cdot$ kg^{-1} $\cdot$ day^{-1} for coherent
  - $R \sim 0.01$ event $\cdot$ kg^{-1} $\cdot$ day^{-1} for incoherent

  For coherent scattering it is required that $A \ll 50$, where A is the detector nucleus mass number
  - usually ^{76}Ge or ^{131}Xe $\Longrightarrow$ large A and incoherent scattering

- Tens of experiments have been carried out and at least several are currently operational
  - detector masses from few 100 grams to few kilograms
  - most used also for double β-decay experimenst: MIBETA, EDELWEISS, H&M, IGEX, CUORICINO, ...
- Techniques
  - ionisation detectors (Ge), solid scintillation detectors (NaI/CsI), gryogenic detectors (Ge), noble gases as liquids (Xe)
- Low counting rates $\Longrightarrow$ extra care for background substraction
  - high-energy neutrons
- Future experiments aims to several hundreds of kilos of detector material
  - GERDA, MAJORANA, EDELWEISS (Ge), ZEPLIN, XMASS-DM, XENON100 (LXe)

7.6 Dark matter

Dark matter experiments – WIMPs – direct experiments – results