DARK MATTER

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Dark Matter in Galaxies - A journal club seminar at your institute


Organising Committee: C. Frigerio Martins, G. Gentile, A. Lapi, S. Leach, C. Tonini
Dark Matter Awareness Week Map

http://www.sissa.it/ap/dmg/
Overview

- Historical Introduction
- The Concept of Dark Matter
- Evidences and Properties
- Direct and Indirect Searches

“Milky Way, M31 and M33”
Background Image Copyright: S. Gottlöber, G. Yepes, A. Klypin, A. Khalatyan from The CLUES Project
Back at those days …

1918: first rotational curve of a galaxy (Andromeda – M31) by F.G. Pease

1922: using Pease result, Ernst Öpik concluded that M31 had up to 3 times as much mass for its light compared to the Milky Way

1932: Jan Oort studied the Milky Way disk in the Solar System neighborhood and found that the mass density was exceeding the density of the visible stars nearby the solar system (by a factor of ~2) → introduction of the concept of some sort of local invisible (dark) matter

1933: Fritz Zwicky estimated the total mass of the Coma cluster by applying the virial theorem to the measured velocities of its galaxies (Zwicky 1933) → he observed very large peculiar velocities leading to an unexpectedly high cluster mass → if the total mass was divided amongst the constituent galaxies, each of them would have an average mass of $5 \times 10^{10} \, M_\odot$, while their average luminous mass was estimated to be only $5 \times 10^{9} \, M_\odot$ → need to postulate the existence of some sort of dark matter in order to maintain the cluster as a bound system
Back at those days …

**Zwicky 1933**

“The average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter. If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter”

1936: Sinclair Smith confirmed Zwicky’s result by applying the same technique to the Virgo galaxy cluster (Smith 1936)
What is DM?

In a galaxy, the radial profile of the gravitating matter $M(r)$ and that of the sum of all luminous components $M_L(r)$ do not match.

A **MASSIVE DARK COMPONENT** is introduced to account for the disagreement.

Its profile $M_H(r)$ must obey:

$$\frac{d \log M(r)}{d \log r} = \frac{M_L(r)}{M(r)} \frac{d \log M_L(r)}{d \log r} + \frac{M_H(r)}{M(r)} \frac{d \log M_H(r)}{d \log r}$$

The DM phenomenon can be investigated only if we accurately measure the distribution of

- *luminous matter*
- *gravitating matter*
In $\Lambda$CDM scenario the density profile for virialized DM halos of all masses is empirically described at all times by the universal NFW profile (Navarro et al. 96, 97):

$$\frac{\rho(r)}{\rho_\text{crit}} \approx \delta \frac{r_s}{r(1 + r/r_s)^2}$$

- More massive halos and those formed earlier have larger overdensities $\delta$.
DM Profiles from N-body Simulations

Dark Matter: *The Movie*

formation of the Via Lactea halo (*Via Lactea Project*)

$z=11.9$

800 x 600 physical kpc

Diemand, Kuhlen, Madau 2006
Historically, the most convincing evidence of the DM existence comes from spiral galaxy rotational curves (actually, we have other - more convincing - evidences than rotational curves)

Newtonian mechanics \(\rightarrow\) circular velocity: 
\[ V_{\text{circ}}^2 = \frac{G M(r)}{r} \]

1940: Oort found that the rotational curve of the galaxy NGC 3115 was not in agreement with that estimated from the luminous component

"It may be concluded that the distribution of mass in the system must be considerably different from the distribution of light... The strongly condensed luminous system appears embedded in a large more-or-less homogeneous mass of great density"
Spiral Galaxies

**ROTATION CURVES (RC):** symmetric circular rotation of a disk characterized by

- sky coordinates of the galaxy centre
- systemic velocity $V_{\text{sys}}$
- circular velocity $V(R)$
- inclination angle $i$
- azimuth angle $\theta$

Circular velocities from spectroscopy (Doppler shift):

- Optical emission lines ($H\alpha$, Na)
- Neutral hydrogen (HI) - carbon monoxide (CO)

$$V_{\text{obs}}(\xi, \eta) = V_{\text{sys}} + V(R) \cos \theta \sin i$$

$$i = \arccos \left( \frac{a}{b} \right)$$
Spiral Galaxies

No RC follows the disk velocity profile
Mass discrepancy at outer radii

Rubin et al. 1980
Spiral Galaxies

The mass discrepancy emerges as a disagreement between light and mass distributions.

\[
\frac{dM}{dr} / \frac{dL}{dr} \neq \text{const} = \left( \frac{M}{L} \right)_* \]

Begeman et al. 1991
Dwarf Spheroidal Galaxies

Low luminosity, gas-free satellites of Milky Way (and M31)

Large mass-to-light ratios (10 to 1000)

Smallest stellar systems containing DM

Most DM dominated objects in the Universe

\[ L = 2 \times 10^3 L_\odot - 2 \times 10^7 L_\odot \] \[ \sigma_0 \sim 7 - 12 \, \text{km s}^{-1} \] \[ M \sim 10^{8-9} M_\odot \] \[ r_0 \approx 130 - 500 \, \text{pc} \]
Dwarf Spheroidal Galaxies

dSph velocity dispersion profiles generally remain flat to large radii

Wilkinson et al. 2009
Dwarf Spheroidal Galaxies

A problem of the (Λ)CDM model/simulations: where are the missing galactic satellites?

“Cosmological models [...] predict that a halo of the size of our Galaxy should have about 50 DM satellites [...] This number is significantly higher than the approximately dozen satellites actually observed around our Galaxy. The difference is even larger if we consider the abundance of satellites in simulated galaxy groups similar to the Local Group. The models predict ~300 satellites inside a 1.5 Mpc radius, while only ~40 satellites are observed in the Local Group.”

Klypin, Kravtsov, Valenzuela & Prada 1999

Nowadays, a bigger number of dSph are known, thanks to the SDSS data, however there are still missing satellites, i.e. the problem is still there!
Clusters of galaxies:

- largest gravitationally bound systems
- \( M \sim 10^{14-15} M_\odot \) and radii of few Mpc
- about 80\% of a cluster mass is in form of DM

Cluster masses can be determined in different ways, e.g.:

- application of the *virial theorem* to the distribution of the radial velocities
- *hydrodynamic* of the X-ray emitting gas
- *gravitational lensing*

→ all of them point to a large fraction of DM in clusters \( M/L \sim 100 - 400 \)
Gravitational Lensing

\textit{(e.g.) The very famous case of the 1E0657-558 aka Bullet Cluster}

The cluster is relatively “close”, at $z = 0.296$; it is composed by two merging clusters passed through each other.

Clowe et al. (2006) mapped the gravitational potential of the system by weak lensing, and compared to the \textit{Chandra} X-ray observations.

As the gas is the dominant part of the baryonic mass, if this was the only mass source, the gravitational potential should trace the baryonic component distribution, which is not the case.

\textbf{This implies that there is a dominant dark massive component}
In the (Λ)CDM, this pattern is perfectly described as primordial quantum fluctuations of the inflation field (Guth 1980).
The CMB power spectrum modeled with data from the WMAP-7 (Komatsu et al. 2010), ACBAR (Reichardt et al. 2009), and QUaD (Brown et al. 2009) experiments.

An astonishing number of informations can be extracted from the power spectrum of the CMB anisotropies!

Detailed study of the first peak gives information about the geometry of the Universe. The ratio of odd to even peaks indicates the Universe's total baryon density while the location of the third peak yields to the density of dark matter.
Structure Formation

Observations suggest that structure formation proceeds hierarchically.

Ordinary baryonic matter had too high temperature and too much radiation pressure left over (from the Big Bang) to collapse and form smaller structures.

DM is the key ingredient because it feels only the gravitational force, therefore the Jeans instability, which permits structures to form, is not opposed by other forces (e.g. radiation pressure).

**DM is needed, as a "compactor" of structure, to produce the structures that we observe today.**

Isosurface of the gravitational potential of the mass distribution in the COSMOS survey (determined from weak gravitational lensing). The field of view covers about nine times the size of the full moon, and the third dimension stretches from redshift 0 to 1.
Baryon Acoustic Oscillations. BAO refers to the clustering of the baryonic matter at a certain length scale due to the acoustic waves (during re-combination era). BAO imprint can be discovered by analyzing the galaxy clustering on large-scale. SDSS discovered it looking at ~ 7000 luminous red galaxies (LRGs), over 3816 square-degrees of sky and out to a redshift of z = 0.47 (Eisenstein et al. 2005).

Primordial Nucleosynthesis. The density of baryons as calculated by Big Bang nucleosynthesis is much less than the observed mass of the Universe based on calculations of the expansion rate. Need to postulate the existence of DM.

Supernovae Ia. In 1998, observations of distant type Ia supernovae indicated the unexpected result that the Universe seems to suffer an accelerating expansion.

(… other stuff that probably I forgot …)

confirm (directly and indirectly) (Λ)CDM picture
Now, I know what you are (still) thinking…

and the answer is **NO**, there are not other theories that explain ALL this stuff…

MOND works “well” on small-scales but does not work on cosmological scales!

Relativistic MOND → TeVeS: they need DM (massive sterile neutrinos) and Λ too!

There are other possibilities (e.g. MOG) but their strength has still to be proved…

ΛCDM VS MOND - Klypin & Prada 2009  
(bars are line-of-sight velocities of SDSS galaxies)

(Λ)CDM is NOT perfect and does not explain everything. Indeed, it is just a model, but is the BEST that we have. It explains the larger number of phenomena and is well proved on different scales in different ways.
Huh?

Now that “we support” DM existence…

What is DM made of?

Dark Matter particle should:

- be **NON – BARYONIC**
- be **COLD**, i.e. non-relativistic speeds
- have **NEUTRAL ELECTRIC and COLOR CHARGE**
- interact only via **GRAVITATIONAL and WEAK forces**
- be **MASSIVE** enough to account for the total matter content
- has **LONG-LIFE** to be present since the early Universe
- be consistent with present observations and constraints
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**WIMPS** are the “**STANDARD**” candidates
How can we find it?

(e.g.) SNOLAB

DIRECTLY

(e.g.) MAGIC

INDIRECTLY
Direct Searches

Principle of Direct Detection

Goodman and Witten: coherent scattering of WIMPs off nuclei (1985)

Galactic WIMP Halo
(\(\rho = 0.3 \, \text{GeV/cm}^3\), 
\(=10^5 \times \text{universal average}\))

\(<V> = 220 \, \text{km/s}\)

\(\sigma_{\chi N}\) probed to-date \(\sim 10^{-44} \, \text{cm}^2\)

What is measured (with different target nuclei and detectors): energy of the recoiling nucleus

What are the challenges: very small energy, very large backgrounds and very small rate
Direct Searches

Particle Detection Channels

- WIMP
  - XENON100
  - XENON10
- DEAP-I
- miniCLEAN
- XMASS
- Scintillation
  - DAMA/LIBRA
  - KIMS
  - ANAIS
- CRESST-II
- ROSEBUD
- Phonons
  - CRESST-I
- Ionization
  - IGEX
  - CoGeNT
  - TEXONO
  - XENON10 (S2)
  - XENON100 (S2)
- Direction
  - DRIFT-II
  - NEWAGE
  - DM-TPC
- Axion Cavities
  - ADMX
- Bubble Nucleation
  - SIMPLE
  - COUPP
  - PICASSO
Direct detection:
Impressive development over the last 10 years, and projected over the next 10...

XENON 10
XMASS (projected)
SuperCDMS (projected)

$10^{-46}$ cm$^2 = 10^{-10}$ pb

from Lars Bergstrom, CTA-LINK, Oxford, November 2010
Indirect Searches

Direct products of annihilation (or decay) of WIMPs are model dependent; however, decay and hadronisation of these products result in:

- high-energy neutrinos
- relativistic electrons, protons and anti-particles
- $\gamma$-rays ($\pi^0 \rightarrow \gamma\gamma$, internal bremsstrahlung, line emission)

and low-energy photons through interaction of electrons:

- with $B$ (synchrotron)
- with interstellar material (bremsstrahlung)
- with CMB (inverse Compton)

so, obviously, the multi-wavelength approach is a very powerful tool!
Indirect Searches

Gamma-ray Fermi-LAT Satellite

The Large Area Telescope is performing a continue all-sky gamma ray survey (100 MeV – 300 GeV). It is a great opportunity to test a number of models predicting gamma-ray emission from DM annihilation or decay and hopefully to detect smoking-gun features…

Cuesta et al. 2010

Abdo et al. 2010

[GeV cm$^{-3}$ kpc sr$^{-1}$]
Indirect Searches

Imaging Atmospheric Cherenkov Telescopes

VERITAS
(USA & England)
2006
4 telescopes
12 meters each
Tucson, Arizona

MAGIC
(Germany, Italy, Spain)
2003
2 telescopes
17 meters each
Canary Islands, Spain

HESS
(Germany & France)
2002
4 telescopes
12 meters each
Windhoek, Namibia

CANGAROO-III
(Australia & Japan)
2004
4 telescopes
10 meters each
Woomera, Australia
Indirect Searches

MAGIC Telescopes Observations

Draco dSph (Albert et al. 2008)

Willman I dSph (Aliu et al. 2009)

Perseus galaxy cluster (Aleksic et al. 2010 × 2)

Comparison of Estimated Integral Flux above 100 GeV Using Equation (1) for the Benchmarks Models Defined in Table 1 and the Upper Limit in the Integral Flux $\Phi^{ul}$ above 100 GeV Coming from MAGIC Data in Units of Photons cm$^{-2}$ s$^{-1}$

<table>
<thead>
<tr>
<th>BM</th>
<th>$\Phi^{model}$ (&gt;100 GeV)</th>
<th>$\Phi^{ul}$ (&gt;100 GeV)</th>
<th>$B^{ul}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I'$</td>
<td>$2.64 \times 10^{-16}$</td>
<td>$9.87 \times 10^{-12}$</td>
<td>$3.7 \times 10^4$</td>
</tr>
<tr>
<td>$J'$</td>
<td>$4.29 \times 10^{-17}$</td>
<td>$5.69 \times 10^{-12}$</td>
<td>$1.3 \times 10^5$</td>
</tr>
<tr>
<td>$K'$</td>
<td>$2.32 \times 10^{-15}$</td>
<td>$6.83 \times 10^{-12}$</td>
<td>$2.9 \times 10^3$</td>
</tr>
<tr>
<td>$F^*$</td>
<td>$2.09 \times 10^{-16}$</td>
<td>$7.13 \times 10^{-12}$</td>
<td>$3.4 \times 10^4$</td>
</tr>
</tbody>
</table>
Summary

Clear and unambiguous evidences for the existence of DM from:

• Rotational Curves
• Cosmic Microwave Background Anisotropies
• Cluster of Galaxies
• Gravitational Lensing

Many other direct and indirect confirmations of the (Λ)CDM picture.

• The distribution of DM halos around galaxies and galaxy clusters shows a complex phenomenology that leads to essential information on the DM nature as well as structure formation processes

• Simulations can reproduce DM halos properties (still open issues)

→ Theory, phenomenology, simulations, experiments play a balanced role in the search for DM

DM is there! We are UNLIKELY missing some fundamental law!
Multimessenger Approach for Dark Matter Detection

MultiDark is a Spanish Project supported by the Ministry of Science and Innovation's Consolider-Ingenio 2010 Programme. It started in December 17, 2009, and will last 5 years.

Ref: CSD2009-00064

Prompted by a call by the Spanish Ministry of Science and Innovation (MICINN) for funding excellence projects grouping together many researchers, most of the Spanish community involved in the field of Dark Matter decided to apply for a common research project. In 2009 the MICINN selected 13 out of a total of 101 proposals in all branches of science. MultiDark was one of these 13.

http://projects.ift.uam.es/multidark/
Dark Matter Awareness Week, 1-8 December 2010

Thanks

http://www.sissa.it/ap/dmg/

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