Introduction to Dark Matter

Paolo Gondolo
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Evidence for cold dark matter

Large Scale Structure

Cosmic Microwave Background

Supernovae

Galaxy Clusters

SDSS (M. Blanton)

Planck

A. Riess

Abell 1689 (HST/ACS, Benitez et al. 2003)

Bullet Cluster

Galaxies

Dwarf Galaxies

M33 rotation curve

M101 (HST; Kuntz et al. 2006)

Markevitch et al. 2004, Clowe et al. 2004

5 10 50 100 v (km/s)

expected from luminous disk

GNMmR

E = \frac{1}{2} m \dot{R}^2 - \frac{G M m}{R} - \frac{1}{6} \Lambda m R^2

\text{(35)}

Evidence for cold dark matter

Planck
Galaxies spin faster or are hotter than gravity of visible mass can support (rotation curves, velocity dispersion)
Galaxies

The method: more mass, faster orbits

Gravity of sun keeps planets in orbit

\[
\frac{GM}{r^2} = \frac{v^2}{r}
\]
Galaxies

Andromeda Galaxy (M31)

Vera Rubin

[Graph showing the rotation curve of NGC 3198]
Galaxies

Galaxies spin faster than gravity of known matter can support

$$M = 1.6 \times 10^{11} M_\odot (r/30 \text{kpc})$$

$$M_{\text{stars+gas}} = 0.4 \times 10^{11} M_\odot$$

$$\frac{M_{\text{total}}}{M_{\text{visible}}} > 4$$

1 pc = 3.08×10^{16} m
Galaxies

Empirical correlations found from thousands of spiral galaxy rotation curves

Salucci+07

3200 rotation curves coadded

Salucci et al 2007
Velocity dispersion measurements reveal dark matter in elliptical galaxies

\[ \sigma^2 \propto \frac{GM}{r} \]

\[ M_{\text{dyn}} \sim 10^{15} \, M_\odot \]

Lokas, Mamon 2003
Dwarf galaxies are dominated by dark matter.
Galaxy clusters are mostly invisible mass (motion of galaxies, gas density and temperature, gravitational lensing)
Galaxy clusters

Different methods lead to the same conclusion: dark matter
Galaxy clusters

Galaxy clusters are mostly dark matter with some gas and a sprinkle of galaxies.
Cold dark matter, *not* modified gravity

The Bullet Cluster

Gravitational potential from weak lensing

Symmetry argument: gas is at center, but potential has two wells.

Galaxies in optical (Hubble Space Telescope)

X-ray emitting hot gas (Chandra)
Fluctuations in the Cosmic Microwave Background (CMB), and Big Bang Nucleosynthesis (BBN) reveal the average mass/energy content of the universe.
corresponding cosmological parameter constraints are shown in Table 5.

Best-fit values and 68% confidence limits for the base

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck+WP+highL+BAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.022161 ± 0.00024</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.11889 ± 0.0017</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04148 ± 0.00056</td>
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<tr>
<td>$\tau$</td>
<td>0.0952 ± 0.013</td>
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<tr>
<td>$n_s$</td>
<td>0.9611 ± 0.0054</td>
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<td>$\ln(10^{10}A_s)$</td>
<td>3.0973 ± 0.025</td>
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<tr>
<td>$\Omega_{\Lambda}$</td>
<td>0.6914 ± 0.010</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.8288 ± 0.012</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>11.52 ± 1.1</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.77 ± 0.77</td>
</tr>
<tr>
<td>Age/Gyr</td>
<td>13.7965 ± 0.037</td>
</tr>
<tr>
<td>$100\theta_*$</td>
<td>1.04163 ± 0.00056</td>
</tr>
<tr>
<td>$r_{drag}$</td>
<td>147.611 ± 0.45</td>
</tr>
</tbody>
</table>

linear perturbation theory

*general relativity and statistical mechanics at $10^4 K \sim 1$ eV/k*
Early universe

Big Bang Nucleosynthesis

Nuclei formation rates depend on the density of baryons (strictly speaking, neutrons)

Agreement between CMB and BBN densities

\[ \Omega_B = \frac{\rho_B}{\rho_{\text{crit}}} \]

\[ \eta = \frac{n_B}{n_\gamma} \]

\[ \frac{\rho}{\rho_{\text{crit}}} \]

\[ \frac{\gamma}{T} \]

\[ \frac{Q}{T} \]

\[ \frac{F}{T} \]

\[ \frac{G}{T} \]

\[ \frac{H}{T} \]

\[ \frac{Y}{T} \]

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The observed energy content of the Universe

- **524±5 pJ/m³** dark energy
- **202±5 pJ/m³** cold dark matter
- **37.2±0.5 pJ/m³** ordinary matter
- **0.04175±0.00004 pJ/m³** photons
- **1 to 4 pJ/m³** neutrinos

**Planck (2013)**

- matter \( p \ll \rho \)
- radiation \( p = \rho / 3 \)
- vacuum \( p = -\rho \)

1 pJ = \( 10^{-12} \) J
The observed energy content of the Universe

- Ordinary matter: $1 \text{ to } 4 \, \text{pJ/m}^3$
- Neutrinos: $37.2 \pm 0.5 \, \text{pJ/m}^3$
- Cold dark matter: $202 \pm 5 \, \text{pJ/m}^3$
- Dark energy: $524 \pm 5 \, \text{pJ/m}^3$
- Photons: $0.04175 \pm 0.00004 \, \text{pJ/m}^3$

$matter \quad p \ll \rho$

$radiation \quad p = \rho/3$

$vacuum \quad p = -\rho$

Planck (2013)

1 pJ = $10^{-12}$ J
An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)
From CMB fluctuations to galaxies

**Cosmic Microwave Background (CMB)**

- Atoms: 380,000 yrs
- Primordial plasma

**Big Bang Nucleosynthesis (BBN)**

- Cold dark matter: few nanoseconds
- Protons and neutrons: few milliseconds
- Atomic nuclei: few seconds — few minutes

**Big Bang Expansion**

13.7 billion years
From CMB fluctuations to galaxies

(27)

T = 1.28 eV

Matter-Radiation Equality

T = 0.26 eV

Recombination

T = 0.2348 meV

Cosmic Microwave Background fluctuations

ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at

Fig. 7.—

Gaussian priors on the distance ratios,

files

the errors in the

alone (see the 3rd column of Table 1 for the maximum likelihood parameters).

The above measurements can be translated into a

improvement over the prior that we adopted for

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From CMB fluctuations to galaxies

Fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.

Baryon Acoustic Oscillations

T=1.28 eV  
T=0.26 eV  
T=0.2348 meV
From CMB fluctuations to galaxies

Fluctuation uncoupled to the plasma have enough time to grow.

More than 80% of all matter does not couple to the primordial plasma!

From CMB fluctuations to galaxies

Fluctuation uncoupled to the plasma have enough time to grow.

More than 80% of all matter does not couple to the primordial plasma!

SDSS

T=0.2348 meV

T=1.28 eV

T=0.26 eV

T=0.2348 meV

(k^3 P(k)/2π^2)

0.1

0.01

0.001

k (h Mpc^-1)

No Dark Matter

SDSS

T=0.2348 meV

T=1.28 eV

T=0.26 eV

T=0.2348 meV

(k^3 P(k)/2π^2)

0.1

0.01

0.001

k (h Mpc^-1)

No Dark Matter

SDSS
From CMB fluctuations to galaxies

Kravtsov, Klypin
Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon.
CDM is an Excellent Model for the Large Scale Structure of the Universe

Hlozek et al. (2012)

Large galaxies

Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

Mass Variance $\Delta M / M = \sqrt{P(k)k^3/(2\pi^2)}$

Mass Scale $M = (4\pi/3)\rho_m(\pi/k)^3$ in $M_\odot$

warm dark matter $(m=250\ eV)$

hot dark matter $(m=1\ eV)$

From CMB fluctuations to galaxies

Hlozek et al 2012
From CMB fluctuations to galaxies

Bode et al 2001
Neutrinos as dark matter

Cosmology provides upper limits on neutrino masses

\[ \sum m < 0.25 \text{ eV} \]

Future reach \(~0.06 \text{ eV}\)
Neutrino as dark matter

- Neutrino oscillations (largest $\Delta m^2$ from SK+K2K+MINOS) place a lower bound on one of the neutrino masses, $m_\nu > 0.086$ eV. 
  *Gonzalez-Garcia et al 2012*

- Cosmology places an upper bound on the sum of the neutrino masses, $\sum m_\nu < 0.23$ eV. 
  *Planck+WP+ACT/SPT+BAO 2013*

- Therefore neutrinos are *hot dark matter* ($m_\nu \ll T_{eq}=1.28$ eV) with density $0.0009 < \Omega_\nu h^2 < 0.0025$

*Detecting this Cosmic Neutrino Background (CNB) is a big challenge*
Small galaxies and dark subhalos

Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

Mass Variance $\Delta M / M = \sqrt{P(k)k^3/(2\pi^2)}$

Large galaxies

Small galaxies

Mass Scale $M = (4\pi/3)\rho_m(\pi/k)^3$ in $M_\odot$

Hlozek et al. 2012
Small galaxies and dark subhalos

Dark-matter-only simulations do not match observations at small scales (~kpc)

They incorrectly predict:
- Too many galactic bulges (too much low angular momentum gas)
- Steep density profiles in dwarf galaxies (cusp/core problem)
- Too dense subhalos/satellites (“too big to fail” problem)
- Too many subhalos/satellites
Small galaxies and dark subhalos
Including models for baryons in the universe can significantly alter the results from structure formation simulations:

- Triaxial halos $\iff$ Oblate/round halos.
- Cuspy dark matter profiles $\iff$ Cored dark matter profiles.
- Cored halos are more easily tidally disrupted $\iff$ Fewer satellites.
- An existing stellar disk $\iff$ An accreted dark disk.
Small galaxies and dark subhalos

**Illustris Simulation**
- Hydrodynamical simulation
- Volume: $(106.5 \text{ Mpc})^3$
- Resolution: 710 pc (DM)/48 pc (gas)
- Solves ‘missing satellite’ and ‘too big-to-fail’ problems. Produces observed galaxy shapes and metallicity.

![Illustris Simulation](image)

**Effect of baryons on dark matter spectrum**

![Effect of baryons on dark matter spectrum](image)
Small galaxies and dark subhalos

1. Calculating the DM dist. | Towards predictive simulations

Illustris

DM-only +Baryons

Read 2014
Small galaxies and dark subhalos

**Cusp/core problem**

Observed density profiles in dwarf galaxies are shallower than predicted with DM only with baryons, density profiles appear to match observations.

*di Cintio et al 2014*

*Oh et al 2011*
Small galaxies and dark subhalos

“Too big to fail” problem

With baryons, the predicted satellites match observations

With DM-only, the predicted satellites are too dense

Brooks, Zolotov 2014
### Small galaxies and dark subhalos

<table>
<thead>
<tr>
<th></th>
<th>Baryons</th>
<th>WDM</th>
<th>SIDM</th>
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<tbody>
<tr>
<td>Bulge-less disk galaxies</td>
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<td>✔️</td>
<td>✔️</td>
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<tr>
<td>The Cusp/Core Problem</td>
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<td>Too Big to Fail</td>
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<tr>
<td>Missing Satellites</td>
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</tbody>
</table>

*Brooks 2014*
Galactic dark matter

Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU

Image by R. Powell using DSS data
Galactic dark matter

The Milky Way disc

- Dwarf < 100 pc
- Solar system is a million times smaller than this!
- ~200 pc
- ~100 pc
- DM only ~ 20 pc

Hydro

Drawing by J. Read
Galactic dark matter

\[
\rho_{\text{dm}} = 0.33^{+0.26}_{-0.075} \text{ GeV cm}^{-3} \quad \rho_{\text{dm}} = 0.25 \pm 0.09 \text{ GeV cm}^{-3}
\]

[volume complete; G12*; R14] [SDSS; Z13]
Galactic dark matter

Dark disks arise from dynamical friction on accreted satellites

Lake 1989; Read et al. 2008/9

Our galaxy had no recent major merger, thus no significant dark disk.
Galactic dark matter

Tidal forces can destroy subhalos and generate tidal streams

Streams of stars have been observed in the galactic halo
SDSS, 2MASS, SEGUE,……..
Galactic dark matter

We know very little about the dark matter velocity distribution near the Sun

![Diagram showing the velocity distribution of dark matter particles in the Milky Way. The distribution is skewed and the median values are indicated.](image)

**Cosmological N-Body simulations including baryons are challenging**

**Read et al 2009**

**Vogelsberger et al 2009**
Evidence for cold dark matter

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Bullet Cluster

Markevitch et al. 2004, Clowe et al. 2004

M33 rotation curve

M101 (HST; Kuntz et al. 2006)

M. Blanton

Evidence for cold dark matter

7.1. Changing the law of gravity?

It has turned out to be very difficult to modify gravity on the various length scales where the dark matter problem resides, but phenomenological attempts have been made to at least explain flat galaxy rotation curves by introducing violations of Newton’s laws (and of general relativity) [75]. Until a satisfactory alternative theory to general relativity has been found it is difficult to further comment on this option. Besides the remarkable success of the ‘standard’ theory in accounting for perihelion motion, redshifts, gravitational lensing and binary pulsar dynamics, the overall consistency of the standard cosmology it provides the basis for, also on the largest scales, is remarkable. An example is the concordance of the mass estimates of galaxy clusters based on galaxy velocity dispersions, gravitational lensing, microwave background distortions and x-ray emission from hot intracluster gas. At present, there does not seem to exist a plausible alternative theory that can match this impressive list of successes.

In principle, there are modifications to Newtonian gravity if there exists a non-zero cosmological constant, since the energy equation for a test particle of mass $m$ at a distance $R$ from a homogeneous sphere of mass $M$ gets an additional term proportional to $\Lambda^{-1}$,

$$E = \frac{1}{2} m \dot{R}^2 - G M m R - \frac{\Lambda m R^2}{6}, \quad (35)$$

(see [6]) showing the attractive nature of the extra force for $\Lambda^{-1} < 0$. However, this additional term is some four orders of magnitude too small to have measurable effects in galactic systems, given the current observational estimates of $\Lambda^{-1}$. In addition, the observationally favoured value of $\Lambda^{-1}$ is positive and thus causes repulsion instead of attraction.
The warning

“For any complex physical phenomenon there is a simple, elegant, compelling, wrong explanation.”