Five Lectures on Dark Matter

First Lecture

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The Big Question

What are the building blocks of our Universe?
The Big Question

What are the building blocks of our Universe?

This question has been around for a while!

Atomic theory by Democritus
(400 BC)
A Very Slow Progress

1600’s
Scientific method by G. Galilei

1800
Experimental evidence for atoms by J. Dalton

1897
Electron discovery by J. J. Thomson (atom not invisible!)

1911
Discovery of the nucleus by E. Rutherford

1970’s
Zoo of elementary particles and the Standard Model

2012
Higgs boson discovery (Standard Model is complete!)
A Magnificent Unified Description

Length (meters)

10^{-15} 10^{-10} 10^{-5} 1 10^5 10^{10} 10^{15} 10^{20} 10^{25}
A Magnificent Unified Description

[Diagram showing a scale ranging from $10^{-15}$ to $10^{25}$ meters with various astronomical and scientific symbols, including quarks, leptons, and forces.]
Is the Game Over?

Have we finally found an answer to the question asked by Democritus more than 2000 years ago?

Can we declare victory?
Is the Game Over?

Have we finally found an answer to the question asked by Democritus more than 2000 years ago?

Can we declare victory?

No!
Dark Matter

Standard Model matter: approximately 5% of the current energy budget.
Dark Matter

Standard Model matter: approximately 5% of the current energy budget

In this five lectures we deal with dark matter

We will review its evidence, theories and experimental searches
Looking at the Invisible?

How can we be sure that dark matter exists?
Looking at the Invisible?

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Observe very carefully the motion of visible objects

Using laws of gravity we find the gravitational potential $\Phi$
Looking at the Invisible?

How can we be sure that dark matter exists?

Observe very carefully the motion of visible objects.

Using laws of gravity we find the gravitational potential $\Phi$.

\[ \nabla^2 \Phi = -4\pi G_N \rho \]

Infer total amount of matter (visible and invisible).
Fritz Zwicky (1930’s)
Careful observation of galaxies within the Coma Cluster

Two independent measurement of the cluster mass... surprise!
Zwicky and the Coma Cluster
Zwicky and the Coma Cluster

METHOD 1

Luminosity conversion into a mass by using known factor (luminous mass)
Zwicky and the Coma Cluster

**METHOD I**
Luminosity conversion into a mass by using known factor (luminous mass)

**METHOD II**
Observation of galaxy velocities and derivation of the potential (gravitational mass)
METHOD I

Luminosity conversion into a mass by using known factor (luminous mass)

METHOD II

Observation of galaxy velocities and derivation of the potential (gravitational mass)

PROBLEM 1

Mass deficit!

\[ M^{(grav)}_{\text{Coma}} \gg M^{(vis)}_{\text{Coma}} \]
Galactic Rotation Curves

Vera Rubin (1970’s)
Careful observation of stellar motion within spiral galaxies

Comparison with expectation based on visible mass… surprise!
Galactic Rotation Curves
Galactic Rotation Curves

GOAL

\( v(r) \)
Galactic Rotation Curves

**GOAL**

\[ v(r) \]

**PREDICTION**

\[ v(r) \propto \begin{cases} r & r \ll r_c \\ r^{-1/2} & r \gg r_c \end{cases} \]
Galactic Rotation Curves
A Dark Matter Halo

Dark matter halo

Halo

Disk
A Dark Matter Halo

\[ m \frac{v^2(r)}{r} = \frac{G_N M(r) m}{r^2} \quad \Rightarrow \quad \rho_{\text{halo}} \propto r^{-2} \]
A Dark Matter Halo

\[ m \frac{v^2(r)}{r} = \frac{G_N M(r)m}{r^2} \Rightarrow \rho_{\text{halo}} \propto r^{-2} \]

N-body simulations

**Isothermal:**  
\[ \rho_{\text{DM}}^{\text{isothermal}}(r) = \frac{\rho_0}{1 + (r/r_c)^2} \]

**NFW:**  
\[ \rho_{\text{DM}}^{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \]

**Einasto:**  
\[ \rho_{\text{DM}}^{\text{Einasto}}(r) = \rho_E \exp \left[ -\frac{2}{\alpha} (r/r_E)^\alpha - 1 \right] \]

Halo density profile for the Milky Way very important for indirect searches (later)
Firm evidence over decades

- Rotation of galaxies
- Velocities of galaxies in clusters
- Velocities of stars in dwarf galaxies
- Hot gas in galaxy clusters
- Galaxy interactions
- Collisions of galaxy clusters
- Gravitational lensing
Gravitational Lensing

We can find evidence for dark matter even beyond the visible galactic disk
Hot gas in galaxy clusters

Clusters are filled with hot gas that does not fall within galaxies.

We observe its X-ray emission.
Hot gas in galaxy clusters

Clusters are filled with hot gas that does not fall within galaxies.
We observe its X-ray emission.

\[
\frac{dp(r)}{dr} = -\frac{G_N M(r) \rho(r)}{r^2}
\]

Hydrostatic equilibrium:
we can infer the distribution of gravitational mass.
Cosmic Microwave Background

Universe 380,000 yrs old,
Temperature 0.3 eV,
Tiny density fluctuations

Species present @ CMB formation:
photons, neutrinos, electrons, protons, dark matter
Cosmic Microwave Background

Universe 380,000 yrs old, Temperature 0.3 eV, Tiny density fluctuations

Species present @ CMB formation: photons, neutrinos, electrons, protons, dark matter

\[ p \quad e^- \quad \gamma \]

Coulomb and Thomson scattering, bound plasma
Sound waves

\[ \chi \]

Free to collapse under its own gravity
Cosmic Microwave Background

Universe 380,000 yrs old,
Temperature 0.3 eV,
Tiny density fluctuations

$\rho_{DM} \simeq 5 \rho_B$

Dark matter must be non-baryonic!
How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?
How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?

**GRAVITATIONAL COLLAPSE**

\[
\frac{\delta \rho}{\rho} \propto \begin{cases} 
\ln(a) & \text{RD} \\
\alpha & \text{MD}
\end{cases}
\]
How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?

**BARYONS ONLY**

\[
\left. \frac{\delta \rho}{\rho} \right|_{\text{today}} \sim \left. \frac{\delta \rho}{\rho} \right|_{\text{CMB}} \frac{a_0}{a_{\text{rec}}} \approx 10^{-5} \times 10^3 \approx 10^{-2}
\]
Structure Formation

How did we go from a highly homogeneous and isotropic universe to galaxies and clusters?

Structure formation can reach the non-linear regime only if there is dark matter!
The Big Question in 2020

What is the dark matter made of?
The Big Question in 2020

Standard Model

Gravity

Dark Matter
The Big Question in 2020

Standard Model

gravity

Dark Matter
The Big Question in 2020

Standard Model

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\mathcal{L}_{SM+DM}
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gravity

Dark Matter

Leptons

Quarks

forces

\( u, c, t, d, s, b, Z, \gamma, W, g, e, \mu, \tau, \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \n...
The Big Question in 2020

In these lectures I will tell you about possible ideas that could end up in that t-shirt

We cannot put anything we want: solid bounds from dark matter searches
What dark matter cannot be

\[ \Omega_{DM}(t_0)h^2 = \frac{\rho_{DM}}{\rho_{\text{crit}}/h^2} = 0.1198 \pm 0.0012 \]
What dark matter cannot be...

**RELIC DENSITY**

\[
\xi_{DM} = \frac{\rho_{DM}}{s(t_0)} = \frac{m_{DM} n_{DM}}{s(t_0)} = m_{DM} Y_{DM} \simeq 4.35 \times 10^{-10} \text{ GeV}
\]
What dark matter cannot be

Reproduce the relic density

**MASS BOUNDS**

**BOSON DM:**
de Broglie wavelength smaller than dwarf galaxies size

\[
\lambda_{DM} = \frac{h}{p} \approx \left( \frac{1\,\text{eV}}{m_{DM}} \right) \times 2.3 \times 10^{-3} \, \text{m}
\]

\[
m_{DM} \gtrsim 10^{-22} \, \text{eV}
\]
What dark matter cannot be

Reproduce the relic density

**MASS BOUNDS**

**FERMION DM:**
Tremaine-Gunn bound
(Pauli exclusion principle)

\[
m_{DM} \gtrsim \left( \frac{9\pi}{4\sqrt{2}} \frac{1}{g \sqrt{MG^3 R^3}} \right)^{1/4} \gtrsim (10 - 100) \text{ eV}
\]

PROBLEM 2
What dark matter cannot be

Reproduce the relic density

“Statistical” bounds on the mass

\[ m_{\text{DM}} \lesssim \begin{cases} 
10^{-6} & m_{\text{DM}} = 10 \text{ GeV} \\
10^{-4} & m_{\text{DM}} = 10 \text{ TeV} 
\end{cases} \]
What dark matter cannot be

Reproduce the relic density

“Statistical” bounds on the mass

Charge neutrality

COLDNESS

Cosmological structures study:
DM particles must have been non-relativistic when
the universe had a temperature $T \sim 1$ keV
This excludes hot relics (next lecture)
What dark matter cannot be

Reproduce the relic density

“Statistical” bounds on the mass

Charge neutrality

Cold relics

Self-Interactions

\[ \frac{\sigma_{\text{self}}}{m} \lesssim 1 \ \text{cm}^2\text{g}^{-1} \]
What dark matter cannot be

Reproduce the relic density

“Statistical” bounds on the mass

Charge neutrality

Cold relics

Self-Interactions

$$\frac{\sigma_{\text{self}}}{m} \lesssim 10^{-24} \text{cm}^2 \text{ TeV}^{-1}$$
What dark matter cannot be

Reproduce the relic density
“Statistical” bounds on the mass
Charge neutrality
Cold relics
Not too-much self-interacting

Stability

\[ \tau_{DM} \gtrsim 5 \times 10^{18} \text{ sec} \]

\[ \tau_{DM} \gtrsim 10^{25-29} \text{ sec} \]

\[ \tau_H \approx 4 \times 10^{17} \text{ sec} \]
What dark matter cannot be

- Reproduce the relic density
- “Statistical” bounds on the mass
- Charge neutrality
- Cold relics
- Not too-much self-interacting
- Enough long-lived

We will see plausible options this week