In Search of Dark Matter

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The Big Idea:
Executive Summary

• We think we know what makes up “regular matter”.

• Most of the matter in the Universe seems to be something else that does not give off (much) light.

→ Dark Matter!!!

• Evidence for dark matter comes from its apparent gravitational influence on regular matter.

• We want to figure out what dark matter is.
Outline

1. Regular Matter

2. Evidence for Dark Matter

3. Dark Matter Searches
Regular Matter
Cat

1 m
Atom

- Cats are made of atoms.
- Every atom consists of a nucleus and a cloud of electrons.
Nucleus

- The nucleus is made of protons and neutrons.
Protons and Neutrons

- Protons and neutrons are made of quarks and gluons.
Elementary Particles

- Electrons, quarks, and gluons do not seem to be made of anything more fundamental. 
  → elementary particles
The Standard Model (SM)

- Our theory of elementary particles (and forces).

- Quarks: u, c, t, d, s, b
- Leptons: ν_e, ν_μ, ν_τ, e, μ, τ

- Force mediators: γ, g, W^+, Z^0

+ General Relativity for gravity
The Standard Model (SM)

- Our theory of elementary particles (and forces).
- The SM specifies what the elementary particles are and how they interact with each other.
- Elementary particles interact through fundamental forces:
  - electromagnetic - electricity and magnetism, light, ...
  - strong - holds nuclei together, binds quarks into nucleons
  - weak - induces radioactive decays
  - gravity - keeps us in our seats
- All “regular matter” is made of SM particles.
The Standard Model (SM)
A Big Question:

• Does this explain that?
Dark Matter ?
The Earth

- The Standard Model explains things on Earth very well.

- Let’s go further away.
The Sun

- Mostly protons, pulled together by gravity.
- Nuclear fusion of protons releases heat to balance gravity.
- The Standard Model explains how this works!
The Solar System

- Planets orbiting the Sun due to gravity.

- The Standard Model still works here!
Galaxies

- A collection of stars held together by gravity. (Ours is the Milky Way.)

$10^{20}$ m
Galactic Rotation

- Many galaxies are disc-shaped and rotate.
- Rotation is balanced by gravitational attraction.
Galactic Rotation

- Compare rotational velocity with visible matter enclosed:

  - Non-visible matter is needed!  
    
    (Vera Rubin, 1970)

  

- 5 \times 10^{20} \text{ m}
Galaxy Clusters

- Galaxies are often found within self-gravitating clusters. (Ours is the Virgo cluster.)

\[ 10^{23} \, \text{m} \]
Galaxy Cluster Velocities

- Compare galaxy velocities in clusters to visible matter:

\[ v_{avg}^2 = \frac{GM_{total}}{R} \]

- Non-visible matter is needed! (Zwicky, 1933)
Gravitational Lensing

- Light is bent by gravity.
Gravitational Lensing and Mass Maps

- Images of galaxies are distorted by matter in between.
- Use the distortions to map the matter density:

- Non-visible matter is needed!
Cosmic Microwave Background Radiation

- The Universe used to be very hot and dense. It expanded and cooled off.
- CMB = leftover photons (i.e. electromagnetic radiation). Their average temperature is $T_{CMB} = 2.725 \text{ K}$.

[COBE 1993]
CMB Temperature Fluctuations

- The CMB temperature is very uniform: $T_{CMB} = 2.725 \text{ K}$. But it has small fluctuations of about 0.01%.
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[Planck 2015]
CMB Temperature Fluctuations

[Planck 2013]
CMB Temperature Fluctuations

- Fluctuation patterns depend on energy content of Universe.

Regular Matter = (4.68 ± 0.05) %

Total Matter = (30.6 ± 0.7) %

[Planck 2015]
Evidence for Extra Non-Visible Matter

1. Galaxy Rotation Curves - $10^{20}$ m
2. Motion in Galaxy Clusters - $10^{23}$ m
3. Gravitational Lensing - $10^{25}$ m
4. CMB Temperature Fluctuations - $10^{26}$ m

- No SM particle (or known form of SM matter) can explain these observations.
**Dark Matter!?**

- DM Hypothesis: the missing stuff is a new form of matter.

- **Dark Matter** can explain the data if:
  1. non-luminous (no electromagnetic or strong charge)
  2. stable (or very long-lived)
  3. non-relativistic very early in the history of the Universe
  4. interacts very weakly with itself and regular matter
  5. gets the right density from cosmic evolution
How Dark Matter Works

- The early Universe was very hot and very uniform. But it had some small fluctuations.
  e.g. CMB

\[ \langle T \rangle \simeq 2.725 \text{ K} \]
How Dark Matter Works

• Regions of higher DM density collapse on themselves through their gravitational self-attraction.
How Dark Matter Works
How Dark Matter Works

Z=28.62

[Andrey Kravtsov]
How Dark Matter Works

- Clumps of DM attract regular matter by gravity.
- Regular matter falls in, contracts by emitting photons, and forms stars and galaxies.
- DM remains as a diffuse “halo”.

[ESO/ L. Calçada]
Dark Matter Searches
What Could the Dark Matter Be?

- All evidence for DM comes from its gravitational influence on visible matter.
- Challenge: gravity is universal.
What Could the Dark Matter Be?

- We don’t know:

  ![Diagram](image)

  [E.K. Park, HEPAP DMSAG, 2007]
WIMP Dark Matter

• WIMP = “weakly interacting massive particle”
  → new particle that connects to the SM by the weak force

• Nice features:
  1. Develops the right density during the cosmological expansion of the Universe for $m_\chi = 100 - 1000 \text{ GeV}$.
  2. Arises in many theories that extend the Standard Model. (e.g. lightest supersymmetric particle, heavy neutrino, ...)
  3. Likely observable in current and future experiments!
Dark Matter Search Methods

• Three main approaches (for WIMP DM):

1. Direct Detection
   → look for DM around us in laboratory experiments

2. Indirect Detection
   → search for effects of DM on astrophysics

3. Colliders
   → create DM in high-energy collisions
Direct Detection of Dark Matter

- If DM exists, we should be surrounded by it.
Direct Detection of Dark Matter

• If DM exists, we should be surrounded by it.

• In our region of the galaxy:

\[\text{DM energy density} = 0.4 \text{ GeV/cm}^3\]
\[\text{average DM speed} = 10^{-3} c = 300 \text{ km/s}\]
Direct Detection of Dark Matter

- DM could scatter in a detector.
- Most current experiments search for nuclear recoils.
Direct Detection of Dark Matter

- Experiments are ongoing at SNOLAB and other sites. No definite DM signals so far.
Indirect Detection of Dark Matter

- DM can annihilate in our galaxy and beyond and produce high-energy cosmic rays.
Indirect Detection of Dark Matter

- Search for excess cosmic rays from DM annihilation!
Dark Matter at Colliders

• DM can be created in high-energy collisions.
  e.g. Large Hadron Collider (LHC)
  \[ \rightarrow \text{proton-proton collisions at } E_{cm} = 13 \, 000 \, \text{GeV} \]
Dark Matter at Colliders

• DM can be created in high-energy collisions. e.g. Large Hadron Collider (LHC)
Dark Matter at Colliders

- DM may be created in high-energy collisions at the LHC.
- Detectors are placed at the proton collision points. ATLAS and CMS are the main detectors for DM searches.
- TRIUMF is an important part of ATLAS.
Dark Matter at Colliders

- DM can be created in high-energy collisions.
  
  e.g. Large Hadron Collider (LHC)
  
  \[ \text{proton-proton collisions at } E_{\text{cm}} = 13\,000\,\text{GeV} \]
Dark Matter at Colliders

- Problem: the LHC detectors can’t detect DM.
- Solution: look for DM together with visible “jet” radiation.
- Signal: jet recoiling against nothing - “missing energy”.

![Diagram of particle interactions showing DM and jet recoiling against nothing]
Dark Matter at Colliders

- Problem: the LHC detectors can’t detect DM.
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\[ \vec{p}_\chi \]

\[ \vec{p}_q \]

\[ \vec{p}_T \]
Summary: In Search of Dark Matter

- DM can explain many observations, but still no discovery!
- Searches are advancing on many fronts:
  - **Direct detection:**
    New detector technologies are improving sensitivity.
  - **Indirect detection:**
    Better observations of cosmic ray are underway.
  - **Collider searches:**
    More data and new search channels at the LHC.
- We hope to find Dark Matter soon!
Dark Matter Opportunities

• DM discovery would teach us something deep about Nature.

• Direct detection experiments may lead to new precision detector technologies.

• DM observation in indirect detection would open a new branch of astronomy.

• Searches for DM may lead to many new discoveries at high-energy colliders like the LHC.
Sizes

- elementary particles: quark, electron, ...
- proton
- nucleus
- atom
- cat
- Earth
- Sun
- Sun → Earth
- galaxy
- galaxy cluster
- grav. lens.
- CMB
Extra Slides
Dark Matter!?

- Energy content of the Universe now:

![Pie chart showing energy content of the Universe with 73% Dark Energy, 23% Dark Matter, <4% Free Hydrogen and Helium, 0.3% Neutrinos, 0.5% Stars, and 0.03% Heavy Elements.]

[Ben Finney 2012]

- Only 5% of matter seems to come from stuff in the SM!
- Missing matter = “Dark Matter”
Baryons

- baryon = proton, neutron, or stuff made from them
- Baryons dominate the energy density of regular matter.
- CMB: \( \frac{\rho_{\text{baryons}}}{\rho_{\text{tot}}} = 0.0468 \pm 0.0005 \)
- Consistent with BBN:

[Cyburt et al. 1997]
Missing Matter #5: Cosmic Structure

• Compare galaxy distributions to simulations of gravitational collapse of cosmic fluctuations.

[2dF GRS 2003] [Millennium-XXL]
What Could the Dark Matter Be?

• All evidence for DM comes from gravitational influence on visible matter.

• Challenge: gravity is universal.
Direct Detection of Dark Matter

• No definite signal so far.
  Limits on DM-nucleus cross sections:

[ Billard, Strigari, Figueroa-Feliciano 2013 ]
Direct Detection of Dark Matter

- No definite signal so far.

Limits on DM-nucleus cross sections:

[Cooley 2014]
Primordial Black Holes as Dark Matter

• How are they formed?

• Very constrained by data:

$$f \ll \frac{\rho_{pbh}}{\rho_{DM}}$$

[Carr, Kuhnel, Sandstad 2016]