Dark Matter

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Dark Matter!

Early History:

- Fritz Zwicky (1933) observed the motions of galaxies in the Coma cluster and
- Zwicky concluded that their trajectories cannot be supported by the visible matter (he used the so-called virial theorem to relate the velocities to the total mass)
- Therefore, some -- most -- matter in Coma must be dark
Coma cluster (100 Mpc away)
Flat rotation curves

- In the 1970s, Vera Rubin and collaborators clinch the evidence for DM by measuring rotation rate of stars in galaxies.
- She found that rotation curves stay flat as you recede from the center of the galaxy.
- Conclusion: the dark halo conspires to “kick in” where the luminous matter stops to make the total curve flat.

Vera Rubin (American, shown measuring spectra)
Measuring the rotation curve

- Galaxies (that is, gas, clouds and stars in them) rotate
- Rotation can only be supported by sufficient mass (see Newton’s laws equation at right)
- Newton’s laws predict that velocity should fall off with square root of radius
- Not observed - velocity stays constant with radius $\Rightarrow$ “flat rotation curves”

$$\frac{mv^2}{r} = \frac{GM_r m}{r^2} \Rightarrow v = \sqrt{\frac{GM_r}{r}}$$
A typical galaxy rotation curve

![Graph showing rotational velocity vs. radius for a galaxy, with annotations for Dark Matter and Luminous components.](image)
Dark Matter is in “halos” around galaxies (and also around clusters)

(invisible) Dark Matter halo

(visible) light from galaxy
“Mass-to-Light ratio” measurements indicate: the bigger the object is, the more DM-dominated it is.
DM “imaged” using weak gravit. lensing

Galaxies

Smooth DM

T. Tyson et al
Bullet cluster: mass and light do not overlap!
Best evidence for DM: fluctuations in the cosmic microwave background (CMB)

red curve: theory with DM
blue points: Planck measurements
Makeup of universe **today**

- **Visible Matter** (stars 0.4%, gas 3.6%)
- **Dark Matter** (suspected since 1930s, established since 1970s)
- **Dark Energy** (suspected since 1980s, established since 1998)
- Also: radiation (0.01%)
Simulation movie
DM cannot be one of these!

Examples:

- **Hadrons**: particle made of quarks
  - **baryons**: 3 quarks
  - **mesons**: 2 quarks
- Leptons and force carries are not made of quarks
DM *could* be one of these supersymmetric particles (there are other possibilities too...)

![Diagram of Standard and SUSY particles](image-url)
Direct and Indirect Searches for Dark Matter:

**Direct detection** - wait for WIMP to scatter off of nuclei in underground detectors

**Indirect detection**: detect products - “normal” particles - of WIMP annihilation in the center of Galaxy (or other galaxies)
WIMPs and Neutrons scatter from the Atomic Nucleus

Photons and Electrons scatter from the Atomic Electrons
Sanford Underground Research Facility (SD)
Upper limits... up until when?

Methods of WIMP Dark Matter detection:

- **Discovery at accelerators** (LHC, ILC…), if kinematically allowed. Can give mass scale, but no proof of required long lifetime.

- **Direct detection** of halo dark matter particles in terrestrial detectors.

- **Indirect detection** of particles produced in dark matter annihilation: neutrinos, photons or antimatter in ground- or space-based experiments.

For a convincing determination of the identity of dark matter, plausibly need detection by at least two independent experiments. For most methods, the background problem is very serious.

**Indirect detection**

\[ \chi \rightarrow \gamma \]  
\[ \chi \rightarrow \bar{p} \]  
\[ \chi \rightarrow e^+ \]  
\[ \chi \rightarrow \nu \]

The Milky Way in gamma-rays as measured by Fermi-LAT

Lars Bergstrom
Indirect detection through $\gamma$-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

VERITAS

CTA (Cherenkov Telescope Array)
Big Questions

1. How sure are we about the evidence for DM?

2. Is DM made up of as-yet undiscovered particles (Weakly Interacting Massive Particles, “WIMPS”)? [as opposed to e.g. modifications of gravity]

3. Will we find the DM?
   When? How sure will we be we found it?

4. When we find DM, then what?