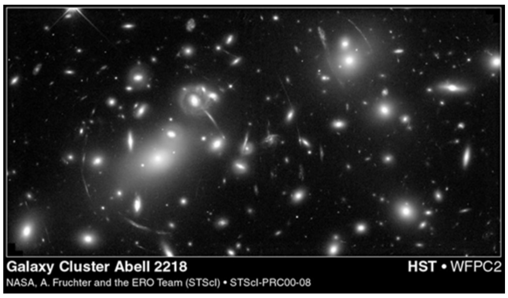
Cosmology 1FA209, 2017
Lecture 6: Dark matter

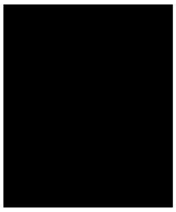


Outline

- What is dark matter?
- How much dark matter is there in the Universe?
- Evidence of dark matter
- Viable dark matter candidates
- Cold dark matter (CDM)
- Problems with CDM
- Search strategies and possible detections
- Alternatives to dark matter

Covers chapter 7 in Ryden + extra stuff

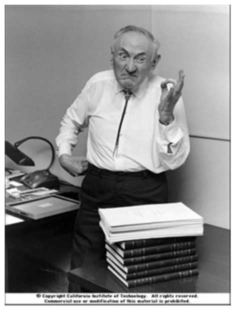
What is Dark Matter?

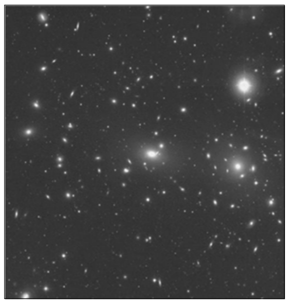


Dark Matter

Luminous Matter

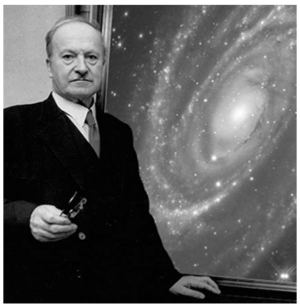
First detection of dark matter





Fritz Zwicky (1933): Dark matter in the Coma Cluster
Often claimed to be the first detection, but…

First detection of dark matter



Recent (2015) "rediscovery" of old paper ⇒
Knut Lundmark (1930): Dark matter in several galaxies, including the Milky Way and Andromeda

How Much Dark Matter is There in The Universe?

$\Omega_M = \rho_M / \rho_c$
Recent measurements:
$\Omega_M \sim 0.3$, $\Omega_\Lambda \sim 0.7$
$\Omega_{Lum} \sim 0.005$

~2% (Luminous)

~98% (Dark)

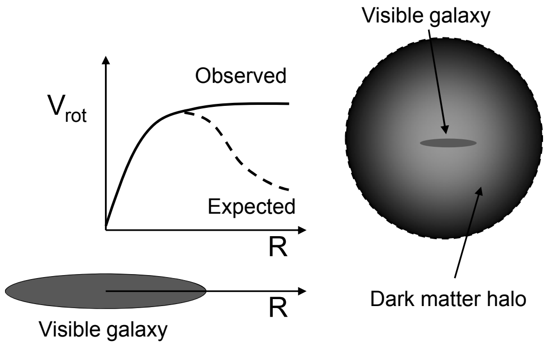
How Do We Know That it Exists?

- Cosmological Parameters + Inventory of Luminous material
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing

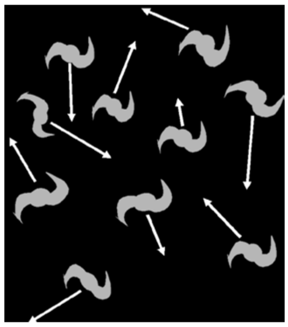
Dynamics of Galaxies I

Galaxy ≈ Stars + Gas + Dust + Supermassive Black Hole + Dark Matter

Dynamics of Galaxies II



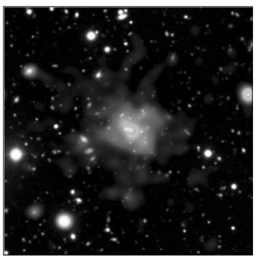
Dynamics of Galaxy Clusters



Balance between kinetic and potential energy →
Virial theorem:

$$M_{\mathrm{vir}} = \frac{\langle v^2 \rangle R}{G}$$

Hot Gas in Galaxy Clusters



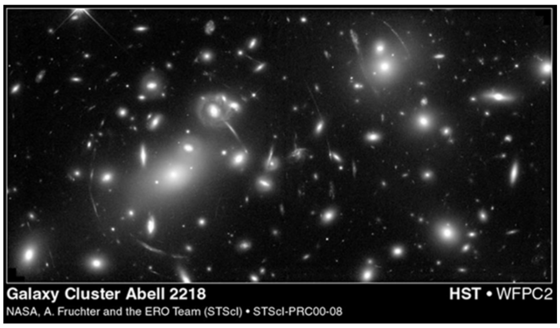
X-ray gas, T=10^7—10^8 K

High mass required to keep the hot gas from leaving the cluster!

If gas in hydrostatic equilibrium → Luminosity and temperature profile → mass profile

Gravitational Lensing

Gravitational Lensing II



Suggestion for Literature Exercise: The Bullet Cluster as a proof* of the existence of dark matter

* Note: Not everybody agrees that this is a proof!

Mass-to-Light Ratios

Mass-to-light: $\frac{M}{L} \left[\frac{M_{solar}}{L_{solar}} \right]$

Observed luminosity

Different choices for M:
M_{tot} = Total mass $\rightarrow$
Dynamical mass-to-light ratio
M_{stars} = Mass of stars & stellar remnants
$\rightarrow$ Stellar mass-to-light ratio

Mass-to-Light Ratios II

What are M/L-ratios good for?
The mass-to-light ratio indicates how dark matter-dominated a certain object is.

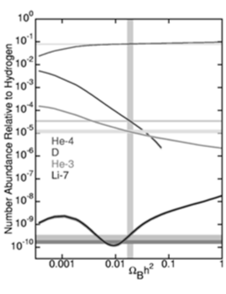
Higher M/L $\rightarrow$ More dark-matter dominated

Typically: $(M/L)_{stars} < 10$ (from models)
But: $(M/L)_{tot} \sim 100$ for galaxies
$(M/L)_{tot} \sim 500$ for galaxy clusters

$(M/L)_{tot} > (M/L)_{stars} \rightarrow$ Dark matter!

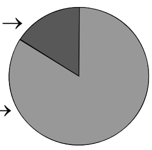
Baryonic and Non-Baryonic Dark Matter I

Baryons: Ordinary matter made out of three quarks, like protons and neutrons



BBNS modelling + measurements of primordial abundances *or* CMBR analysis $\rightarrow$ $\Omega_{baryons} \approx 0.045$

$\Omega_{Baryonic} \approx 0.045 \rightarrow$



$\Omega_{Non\text{-}baryonic} \approx 0.25 \rightarrow$

$\Omega_M = \Omega_{Baryonic} + \Omega_{Non\text{-}baryonic} \approx 0.3$

MACHOs and WIMPs

- MACHO = MAssive Compact Halo Object
- WIMP = Weakly Interacting Massive Particle

A Few Viable Dark Matter Candidates

Very Popular!

- Supersymmetric particles
- Axions
- Sterile neutrinos
- Primordial black holes
- Preon stars
- Quark nuggets
- Mirror matter
- Matter in parallel branes
- Kaluza-Klein particles

Hot and Cold Dark Matter

- Hot Dark Matter (HDM)
  - Relativistic early on (at decoupling)
- Cold Dark Matter (CDM)
  - Non-relativistic early on (at decoupling)
  - The standard model for the non-baryonic dark matter
  - Successful in explaining the formation of large scale structure

Additional Assumed CDM Properties

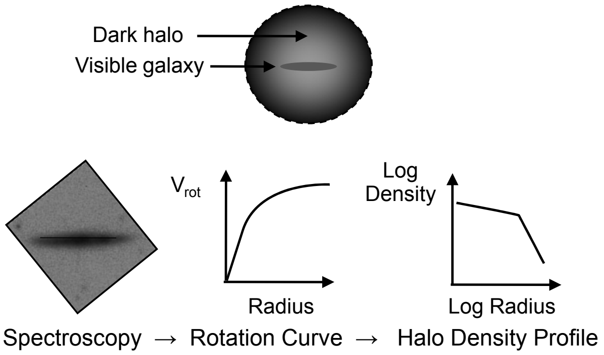
- Collisionless – interacts mainly through gravity
- Dissipationless – cannot cool by radiating photons
- Long-lived particles
- Behaves as perfect fluid on large scales
- Adiabatic primordial density perturbations, following a scale-invariant power spectrum

More in structure formation lecture!

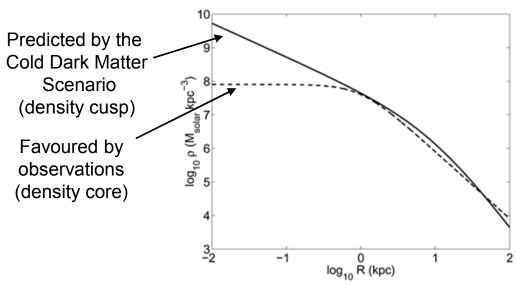
Problems with CDM

- Dark halo density profiles
- Dark halo substructure
- Dark halo shapes
- The angular momentum problem

Dark Halo Density Profiles I



Dark Halo Density Profiles II



Dark Halo Density Profiles III

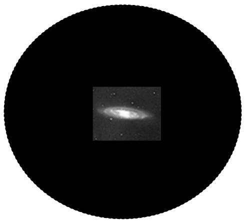
But there are plenty of complications… ↙ Currently the favoured solution

- Baryonic processes alter density profile?
- Non-spherical dark matter halos?
- Best target galaxies do not sit in typical dark halos?
- N-body simulations responsible for the predicted CDM halo profile prediction not reliable?

Dark Halo Substructure I

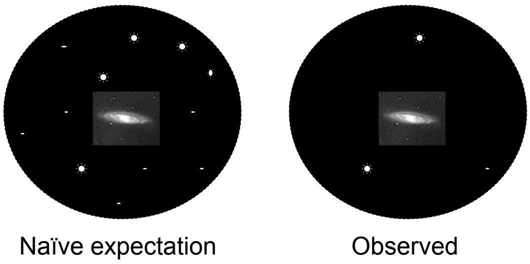
The dark halos around galaxies form the merger of smaller halos, but many remnants of the smaller halos survive →
The dark halos of galaxies are not perfectly smooth!

~10 % of the dark matter is in clumps
(a.k.a. subhalos or halo substructure)



Dark Halo Substructure II

Should not dwarf galaxies form inside the subhalos?



A factor of 10—100 too few satellite galaxies around the Milky Way!

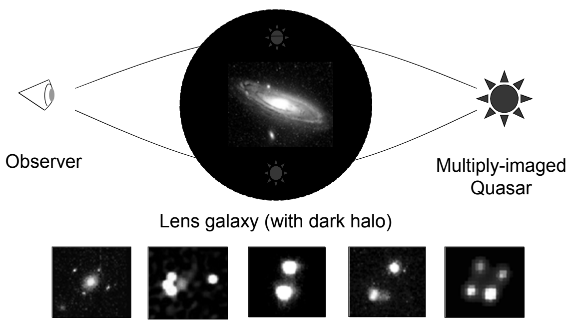
Dark Halo Substructure III

The solution: Dark galaxies?

- Dark galaxy: A dark subhalo which either lacks baryons, or inside which the baryons form very few stars
- Possible detections exist of galaxies with very high mass-to-light ratios (M/L≥1000), but not yet in sufficient numbers to solve the problem

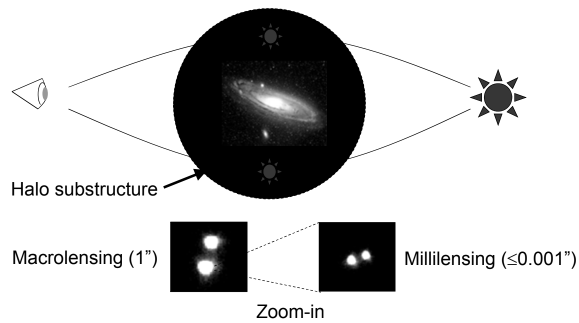
How to detect halo substructure

Dark halos can cause image splitting in quasars on angular scales of ~ 1 arcsecond (macrolensing)



How to detect halo substructure II

Halo substructure can cause additional splitting of each image on angular scales of ~0.001 arcseconds (millilensing)



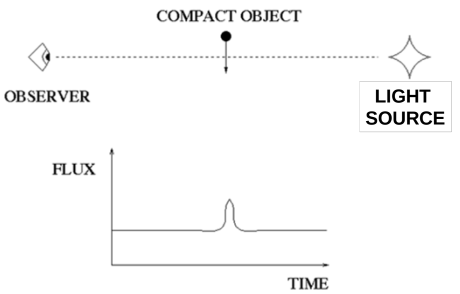
Alternatives to CDM

- Warm dark matter
- Mixed dark matter (cold + hot)
- Self-interacting dark matter
- Decaying dark matter
- Alternative theories of gravity

How to Search for Dark Matter Particles

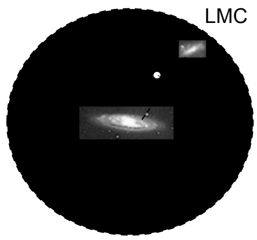
- Gravitational microlensing by MACHOs
- WIMP direct detection
  - Recoil in detector
  - Annular modulation
- WIMP indirect detection
  - Cosmic rays from annihilating WIMPs
  - Neutrinos from WIMP annihilation in Sun/Earth
  - Photons (gamma, radio) from WIMP annihilation in the Galactic Centre

Gravitational Microlensing by MACHOs



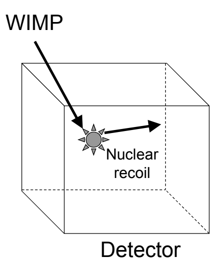
Possible detections I

MACHO project: monitoring of 12×10^6 stars in the Large Magellanic Cloud



Very controversial detection of $M_{compact}$~10^{-1} M_{solar}, constituting ≈20% of the dark halo

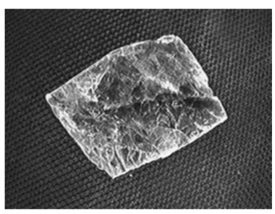
Direct WIMP detection



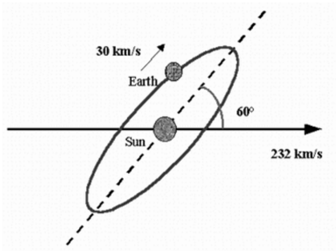
Problem: Background of other rare reactions

Direct WIMP Detection in Ancient Mica

WIMP recoils cause chemical changes in ancient mica
→ Natural detector with integration time ~ 1 Gyr



Annular Modulation

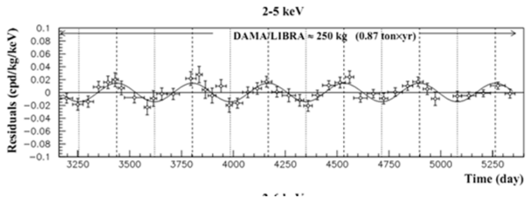


WIMP wind from the dark halo
should show seasonal variations!

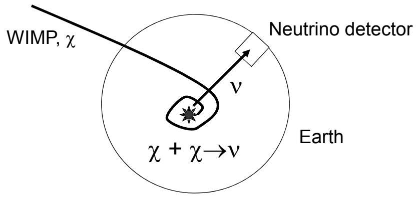
Possible detections II

WIMP search by the DAMA experiment

Detected annular modulation signature
→ $\geq 10^{-3}$ of halo fraction in WIMPs



Indirect WIMP detection by Neutrinos from the Sun/Earth



WIMPs may accumulate in the
potential well of the Sun/Earth,
and annihilate to produce neutrinos

Is There no Alternative to Dark Matter?

”I invite the reader (...) to test whether he/she is not left with some uneasiness as our wonderful 'standard' cosmology seems in fact to be so far essentially based on

a) a *Dark Matter* we do not detect
b) a *Dark Energy* we do not understand
c) a fraction of Baryons we cannot completely find!

Yet everything seems to work;
isn't this reminiscent of epicycles?“

L. Guzzo (2002)

MOND
(MOdified Newtonian Dynamics; Milgrom 1984)

Newtonian dynamics: $a = MG/r^2$

MOND: $a^2/a_0 = MG/r^2$
in the limit of small accelerations

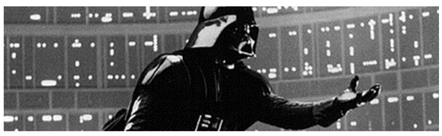
→ $\mu(a/a_0)a = MG/r^2$

where $\mu(x) \approx 1$ when $x \gg 1$

$\mu(x) \approx x$ when $x \ll 1$

MOND II

From Stacy McGaugh’s old homepage:



”You do not know the Power of the Dark Side. Join me, and together we can use dark matter to make galaxy rotation curves flat.’ I often hear this sort of paternalistic line from well intentioned senior astronomers. My response is the same as Luke's, with analogous consequences for my career.”

Known problems with MOND

- Original MOND: Phenomenological extension of Newtonian gravity → No predictions for e.g. gravitational lensing or cosmic expansion

  Fails to explain the dynamics of galaxy clusters – some dark matter is still required
- Fails to explain difference between systems of similar baryonic masses, e.g. globular clusters and dwarf galaxies

Suggestion for literature Exercises: Alternative theories of gravity vs. Dark matter

- Many examples (pick _one_):
  - MOND – Lots of work done. Fairly easy to understand at an undergraduate level
  - MOdified Gravity (MOG) – Slightly more technical. Requires some understanding of tensors.
- Can GR explain rotation curves without dark matter?