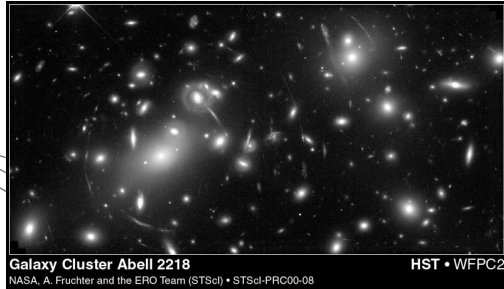


## Cosmology AS7009, 2009 Lecture 6



## Outline

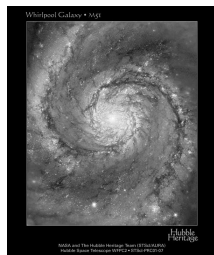
- What is dark matter?
- How much dark matter is there in the Universe?
- Evidence of dark matter
- Viable dark matter candidates
- Cold dark matter (CDM)
- Problems with CDM
- Search strategies and possible detections
- Alternatives to dark matter

Covers chapter 8 in Ryden + extra stuff

## What is Dark Matter?

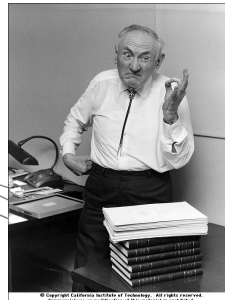


Dark Matter

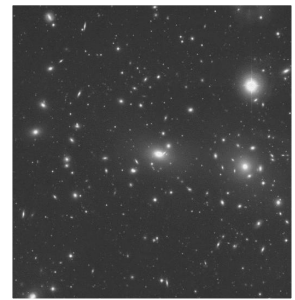


Luminous Matter

## First detection of dark matter



Fritz Zwicky (1933): Dark matter in the Coma Cluster



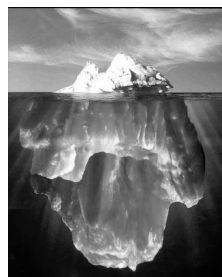
## How Much Dark Matter is There in The Universe?

$$\Omega_M = \rho_M / \rho_c$$

Recent measurements:

$$\Omega_M \sim 0.3, \Omega_\Lambda \sim 0.7$$

$$\Omega_{Lum} \sim 0.005$$



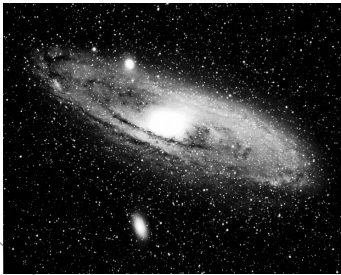
~2%  
(Luminous)

~98%  
(Dark)

## How Do We Know That it Exists?

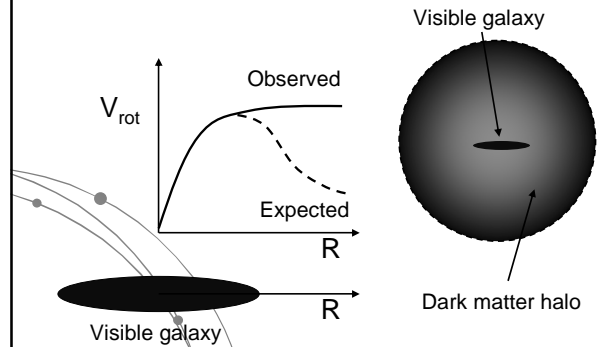
- Cosmological Parameters + Inventory of Luminous material
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing

## Dynamics of Galaxies I

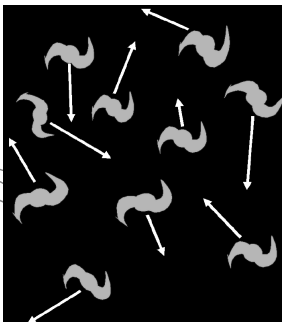


Galaxy  $\approx$  Stars + Gas + Dust +  
Supermassive Black Hole + Dark Matter

## Dynamics of Galaxies II



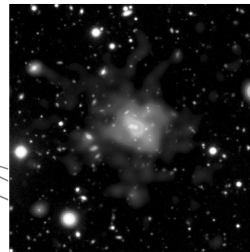
## Dynamics of Galaxy Clusters



Balance between  
kinetic and potential  
energy  $\rightarrow$   
Virial theorem:

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

## Hot Gas in Galaxy Clusters



X-ray gas,  $T=10^7-10^8$  K

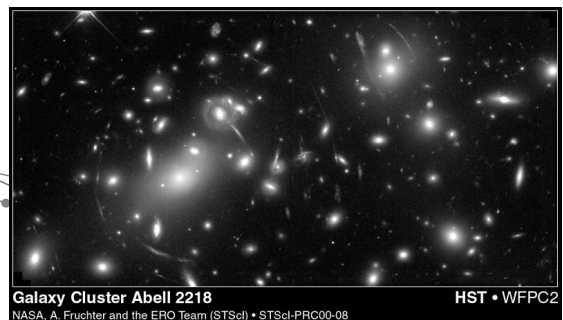
High mass required to  
keep the hot gas from  
leaving the cluster!

If gas in hydrostatic  
equilibrium  $\rightarrow$   
Luminosity and  
temperature profile  $\rightarrow$   
mass profile

## Gravitational Lensing



## Gravitational Lensing II



Galaxy Cluster Abell 2218

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

HST • WFPC2

## 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

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

Observed luminosity

Different choices for M:

$M_{\text{tot}}$  = Total mass →

Dynamical mass-to-light ratio

$M_{\text{stars}}$  = Mass of stars & stellar remnants

→ 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 → More dark-matter dominated

Typically:  $(M/L)_{\text{stars}} < 10$  (from models)

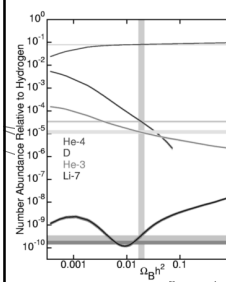
But:  $(M/L)_{\text{tot}} \sim 100$  for galaxies

$(M/L)_{\text{tot}} \sim 500$  for galaxy clusters

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

## Baryonic and Non-Baryonic Dark Matter I

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

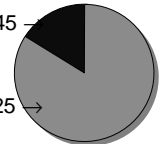


BBNS modelling + measurements  
of primordial abundances  
or CMBR analysis →  $\Omega_{\text{baryons}} \approx 0.045$

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

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

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



## Baryonic and Non-Baryonic Dark Matter II

Still missing in the local Universe:

- About 1/3 of the baryons →

$\Omega_{\text{DM, baryonic}} \sim 0.015$

But note: The missing baryons *may* have  
been detected at high redshift

- Essentially all of the non-baryons →

$\Omega_{\text{DM, non-baryonic}} \sim 0.25$  (assuming  $\Omega_{\text{M}} = 0.3$ )

## MACHOs and WIMPs


- MACHO = MASSive Compact Halo Object

- WIMP = Weakly Interacting Massive Particle


But beware of misconceptions!

## A Few Viable Dark Matter Candidates

### Baryonic

- Faint stars
- Fractal  $H_2$
- Warm/hot intergalactic gas
- Hot gas around galaxies
- Rydberg matter 

### Non-baryonic\*

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

\* or evading current constraints on the cosmic baryon density

## 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

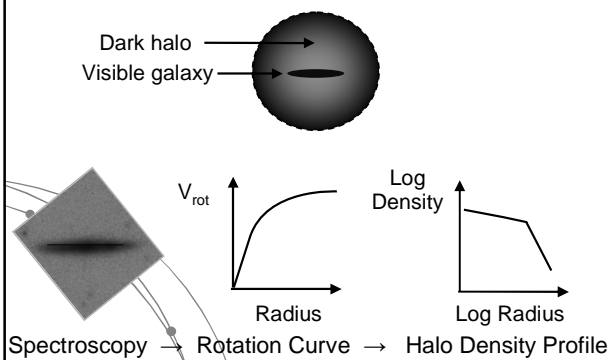
- Collisionless – interacts mainly through gravity
- Dissipationless – cannot cool by radiating photons
- Long-lived particles
- Behaves as perfect fluid on large scales
- Adiabatic primordial density perturbations, following a scale-invariant power spectrum

More in structure formation lecture!

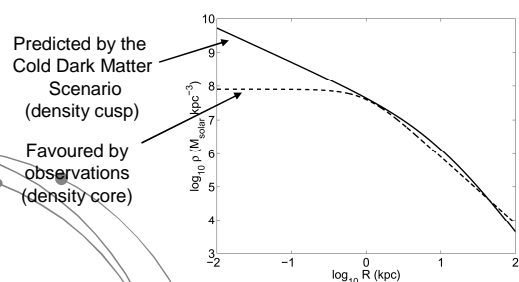
## Problems with CDM

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

## Dark Halo Density Profiles I



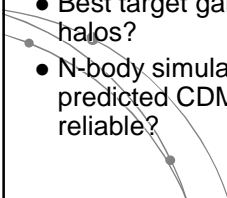
## Dark Halo Density Profiles II



## Dark Halo Density Profiles III

But there are plenty of complications...

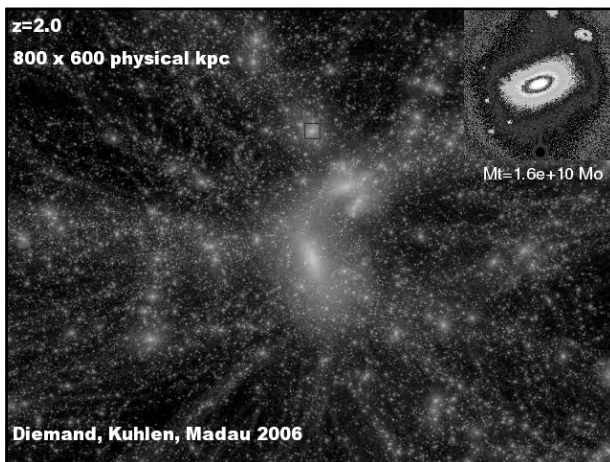
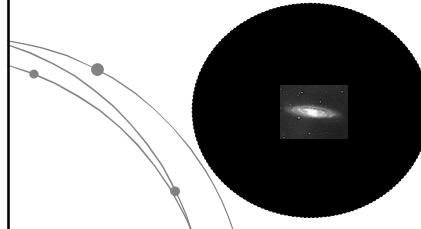
- Non-spherical dark matter halos?
- Central part dominated by dark baryons instead of CDM?
- Best target galaxies do not sit in typical dark halos?
- N-body simulations responsible for the predicted CDM halo profile prediction not reliable?



## Dark Halo Substructure I

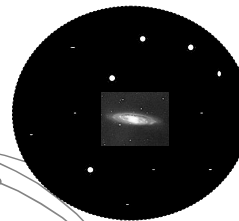
The dark halos around galaxies form the merger of smaller halos, but many remnants of the smaller halos survive → The dark halos of galaxies are not perfectly smooth!

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

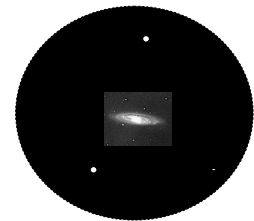


## Dark Halo Substructure II

Should not dwarf galaxies form inside the subhalos?



Naïve expectation



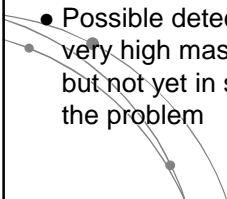
Observed

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

## Dark Halo Substructure III

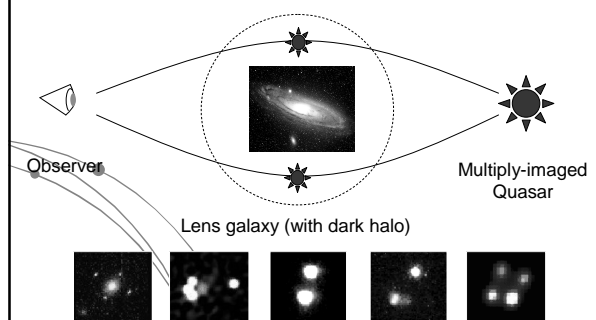
The solution: Dark galaxies?

- 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 ( $M/L \geq 1000$ ), but not yet in sufficient numbers to solve the problem



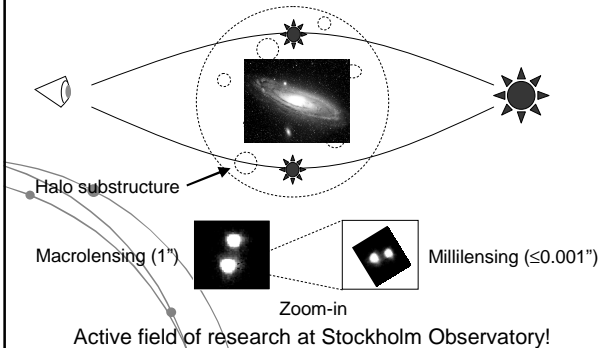
## How to detect halo substructure

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  $\sim 0.001$  arcseconds (millilensing)



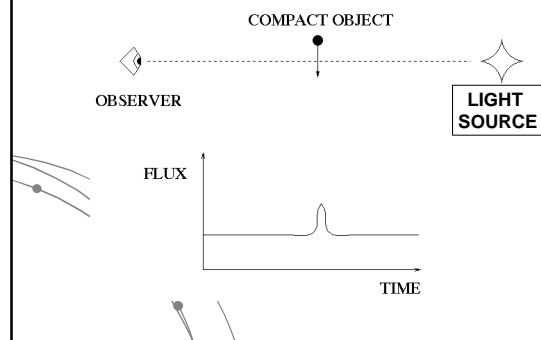
## Alternatives to CDM

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

## How to Search for the Dark Matter Particles

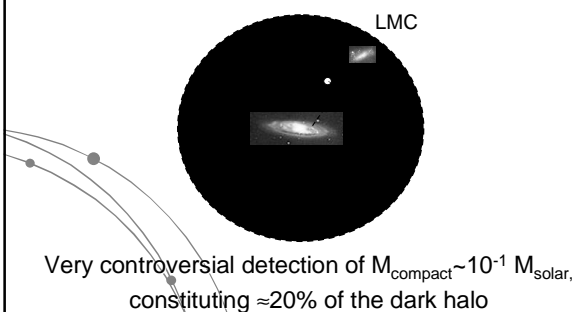
- Gravitational microlensing by MACHOs ←
- WIMP direct detection
  - Recoil in detector ←
  - Annular modulation ←
- WIMP indirect detection
  - Cosmic rays from annihilating WIMPs
  - Neutrinos from WIMP annihilation in Sun/Earth ←
  - Photons (gamma, radio) from WIMP annihilation in the Galactic Centre

## Gravitational Microlensing by MACHOs

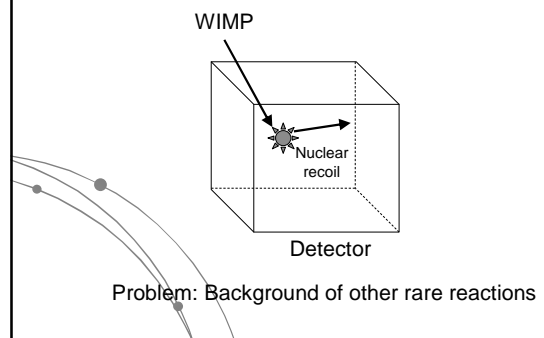


## Possible detections I

MACHO project: monitoring of  $12 \times 10^6$  stars in the Large Magellanic Cloud

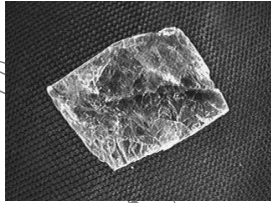


## Direct WIMP detection

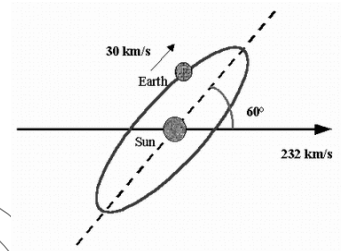


## Direct WIMP Detection in Ancient Mica

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



## Annular Modulation

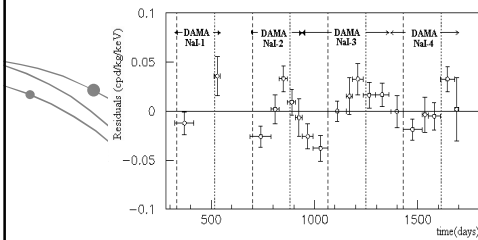


WIMP wind from the dark halo  
should show seasonal variations!

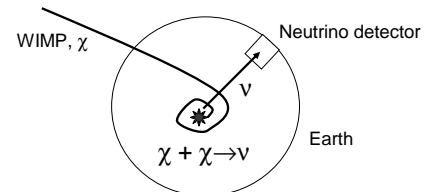
## Possible detections II

### 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 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  
Solved by Bekenstein (2004)!
- 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?