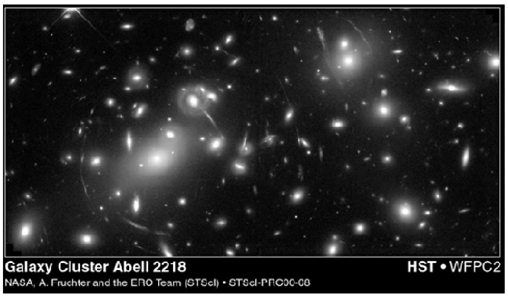
Galaxies AS7007, 2012
Lecture 3: Dark matter in galaxies



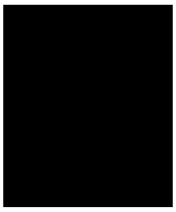
Outline I

- What is dark matter?
- How much dark matter is there?
- How do we know it exists?
- Dark matter candidates
- The Cold Dark Matter (CDM) model

Outline II

- Dark halos and subhalos
- Problems with CDM
- Dark matter annihilation
- Missing baryons

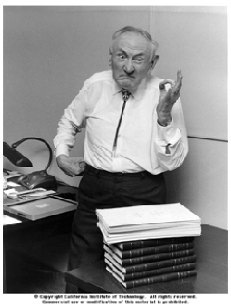
What is Dark Matter?

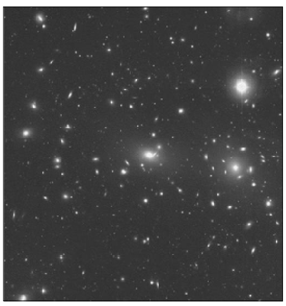


Dark Matter

Luminous Matter

First detection of dark matter





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

How Much Dark Matter is There?

$\Omega_M = \rho_M / \rho_c$

Recent measurements:

$\Omega_M \sim 0.27$

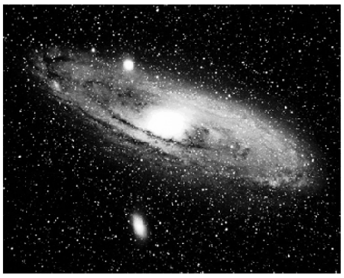
$\Omega_\Lambda \sim 0.73$

$\Omega_{Lum} \sim 0.005$

How Do We Know it Exists?

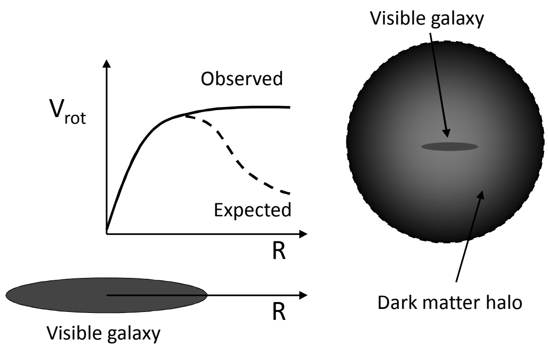
- Cosmological Parameters + Inventory of luminous material
- Dynamics of galaxies
- Dynamics and gas properties of galaxy clusters
- Gravitational Lensing

Dynamics of Galaxies I

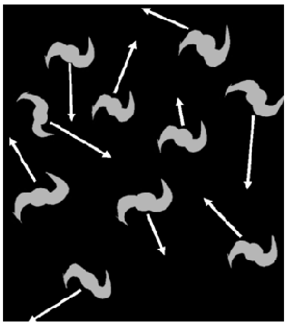


Galaxy ≈ Stars + Gas + Dust + Supermassive Black Hole + Dark Matter

Dynamics of Galaxies II



Dynamics of Galaxy Clusters

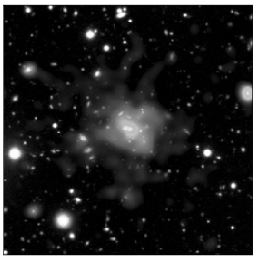


Balance between kinetic and potential energy → Virial theorem:

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

Check out Sect. 6.2.5 in Schneider for details

Hot Gas in Galaxy Clusters



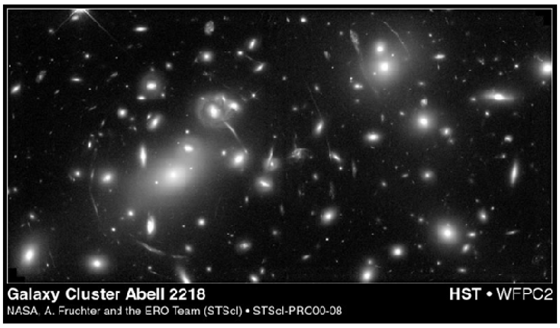
High mass required to keep the hot gas from leaving the cluster!

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

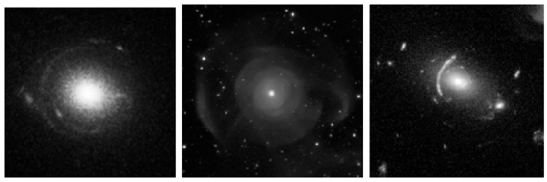
X-ray gas, T=10^7—10^8 K

Gravitational Lensing

Gravitational Lensing II



Intermission: One of these is not a lens – which one?



Baryonic and non-baryonic matter

$\Omega_M \sim 0.27$

$\Omega_{baryons} \sim 0.04$

Most of the matter (85%) in the Universe shares no resemblance to the matter we know from everyday life!

Particles with 3 quarks, like the proton and neutron

A Few Non-baryonic* Dark Matter Candidates

Popular!

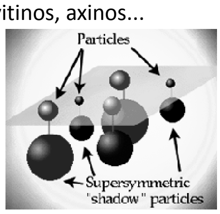
- Supersymmetric particles
- Axions
- Sterile neutrinos
- Primordial black holes
- Preon stars
- Quark nuggets
- Mirror matter
- Matter in parallel branes
- Kaluza-Klein particles

* or evading current constraints on the cosmic baryon density

What is supersymmetry (SUSY)?

- A high-energy extension of the standard model
- SUSY predicts a symmetry between bosons and fermions:
  Standard particle ↔ SUSY partner
  - fermion (e.g. quark) ↔ boson (e.g. squark)
  - boson (e.g. photon) ↔ fermion (e.g. photino)

  → Zoo of new particles: selektrons, sneutrinos, gluinos, Higgsinos, gravitinos, axinos...



Weakly Interacting Massive Particles (WIMPs)

- Interactions through weak force and gravity only → dark matter transparent
- Weak-scale interactions → right cosmological density to be dark matter ("The WIMP miracle")
- Massive (GeV to TeV scale)
- No WIMP candidate in standard model of particle physics
- The canonical WIMP is a SUSY particle (often a neutralino), but not all WIMP candidates are SUSYs

WIMPs in your morning coffee

Generic assumptions (~100 GeV WIMPs) →
Handful of WIMPs in an average-sized coffee cup

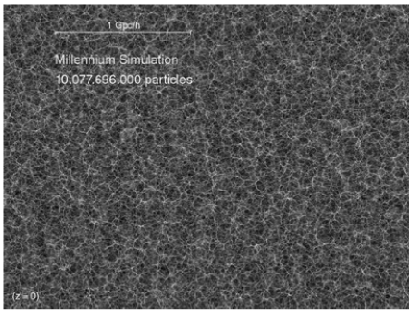
Hot and Cold Dark Matter

- Hot Dark Matter (HDM)
  - Relativistic early on (at decoupling)
  - Ruled out by observations
- 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 (galaxies, galaxy clusters, voids and filaments)

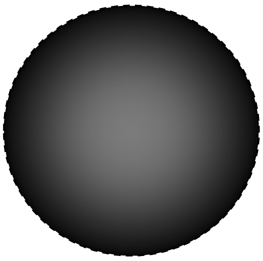
Additional Assumed CDM Properties

- Collisionless – interacts *mainly* through gravity
- Dissipationless – cannot cool by radiating photons
- Long-lived particles
- Behaves as perfect fluid on large scales

The Universe according to CDM



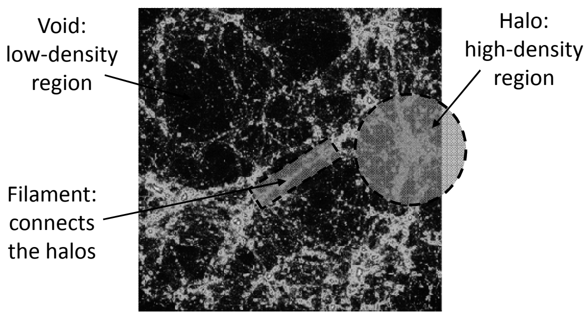
The dark matter halo



Schematic illustration

What it looks like in
actual N-body simulations

Voids, halos and filaments

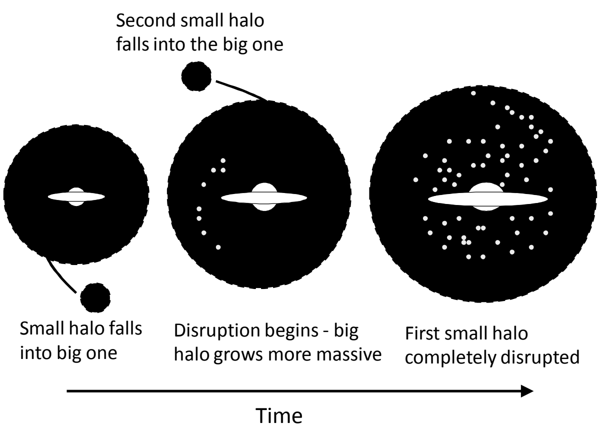


A hierarchy of dark matter halos

- All galaxy clusters and *almost* all galaxies form at the centre of dark matter halos
- Halo mass range: ~10^{-6} – 10^{15} Msolar
  - $M_{halo} > 10^{13}$ Msolar: Galaxy groups and clusters
  - $M_{halo} \sim 10^{11}$–10^{13} Msolar: Large galaxies
  - $M_{halo} \sim 10^{8}$–10^{11} Msolar: Dwarf galaxies
  - $M_{halo} < 10^{8}$ Msolar: ???
    Largely untested part of the CDM paradigm…
    The very first stars are predicted to form in these halos at z>15, but where are these halos now?

A hierarchy of dark matter halos II

- Halo mass range: ~10^{-6} – 10^{15} Msolar
  - Lower cutoff depends on detailed properties of the dark matter particles, could be 10^{-12} to 10^{7} Msolar, depending on the model
  - Mass function shape: Always far more low-mass halos than high-mass ones
  - Low-mass halos assemble first, then merge to form high-mass ones



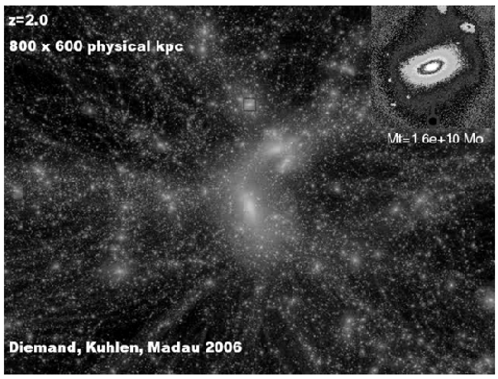
The formation of a halo

The Aquarius simulation (Springel et al. 2008)

Subhalos

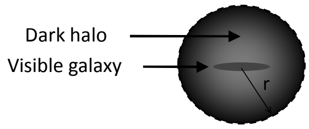
- Massive halos are assembled by the accretion of halos of lower mass
- Many accreted halos get disrupted in the tidal field of the halo they fell into, but some temporarily survive in the form of subhalos
- On average ~10% of the mass of a halo is in the form of subhalos at the current time

The tumultuous life of a subhalo



Intermission: What does this picture have to do with subhalos?

Dark halo density profiles I



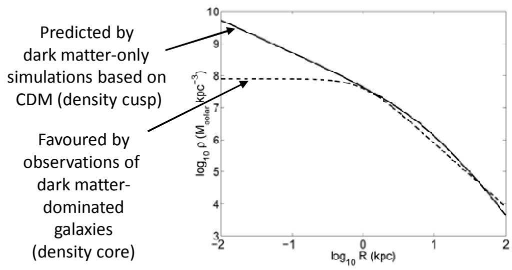
Famous dark matter-only, N-body simulations by Navarro, Frenk & White (1996, 1997)→

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

$\rho \propto r^{-1}$ at small r
$\rho \propto r^{-3}$ at large r

NFW profile now slightly outdated, but still in active use

CDM problem I : The core/cusp issue



Possible solution:
Baryonic processes (supernova explosions, "feedback") may have altered the CDM density profile (Governato et al. 2010, Nature)

Density profiles of real galaxies I

- Singular Isothermal sphere

$$\rho_{\rm SIS}(r) = \frac{\rho(r_0)}{(r/r_0)^2}$$

$\sigma(r)$ = constant
$\rho(r) \to \infty$ when $r \to 0$
$M(<r) \to \infty$ when $r \to \infty$
Outer truncation required!

Works reasonably well for massive galaxies acting as strong gravitational lenses, probably due to baryon-domination in the centre

Density profiles of real galaxies II

- Pseudo-isothermal sphere (cored)

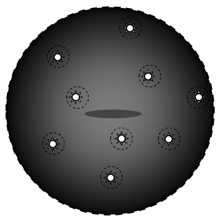
$$\rho_{\rm PIS}(r) = \frac{\rho_0}{1+(r/r_c)^2}$$

$\rho(r) \to \rho_0$ when $r \to 0$
$M(<r) \to \infty$ when $r \to \infty$
Outer truncation necessary!

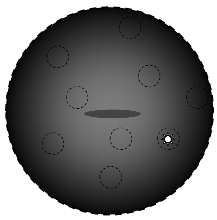
Works reasonably well for dark matter-dominated galaxies (dwarfs and low surface brightness galaxies)

CDM problem II: Missing satellites

Should not dwarf galaxies form inside the subhalos?



Naïve expectation



Observed

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

CDM problem II: Missing satellites

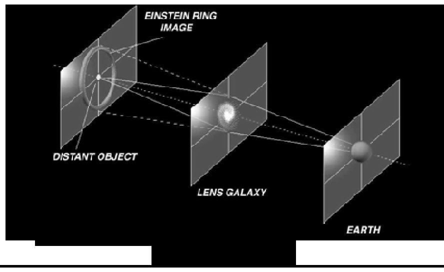
Possible solutions:

- Vanilla CDM incorrect – alternative models (e.g. warm dark matter) produce fewer subhalos
- Star formation in low-mass subhalos inefficient → lots of ultrafaint or completely dark subhalos awaiting detection around the Milky Way

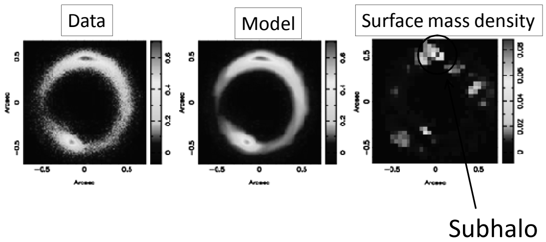
CDM problem II: Missing satellites

Confusing input from gravitational lensing:

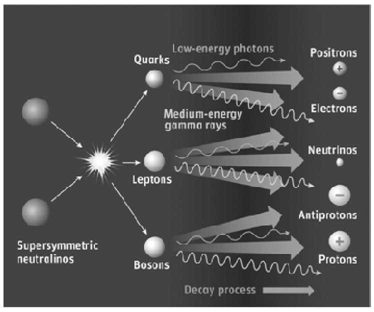
- Lensing requires *more* subhalos, or at least a different halo mass function than predicted by CDM



Vegetti et al. (2012, Nature)

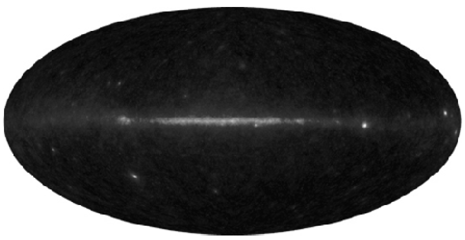


WIMP annihilation



WIMPs predicted to annihilate in regions where the CDM density is high → Subhalos should glow in gamma-rays

Fermi Gamma-ray Telescope



Launched in 2008, but still no clear-cut signatures of WIMP annihilation in subhalos

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 → Dynamical mass-to-light ratio

M_{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 $\rightarrow$ More dark-matter dominated

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

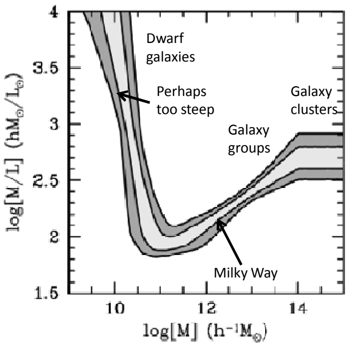
$(M/L)_{tot}$ ~100 for large galaxies

$(M/L)_{tot}$ ~ 300 for galaxy clusters

$(M/L)_{tot}$ ~ 1000 for ultrafaint dwarf galaxies

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

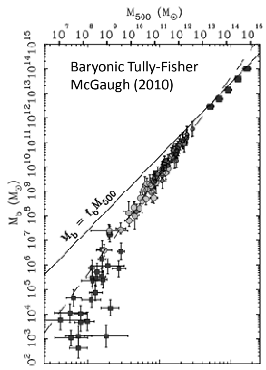
Mass-to-Light Ratios III



Model by Van den Bosch et al. (2005)

Baryon fractions

- About 1/3 of the cosmic baryons still unaccounted for at z=0
- Baryon fraction f_b below cosmic average in nearly all galaxies
- Some of the missing baryons may be in the warm intergalactic medium (in between halos)



Tidal dwarf galaxies

- TDGs form out of shredded disk material
- Only type of galaxy predicted to be nearly CDM-free
- But M/L high $\rightarrow$ Some form of dark matter still present?
- Dark baryons?