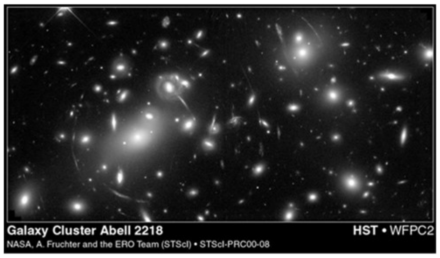
Physics of Galaxies 2018
10 credits
Lecture 3: Dark matter in galaxies



Outline I

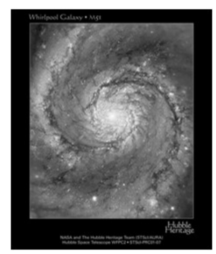
- What is dark matter?
- How much dark matter is there?
- How do we know it exists?
- Dark matter candidates
- The Cold Dark Matter (CDM) model

Outline II

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

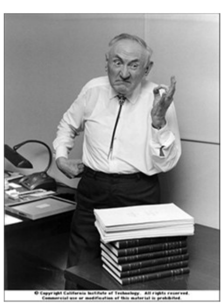
What is Dark Matter?

Dark Matter



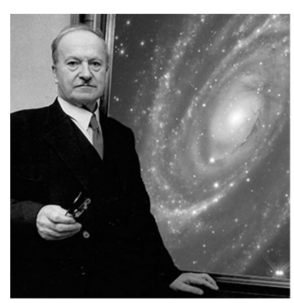
Luminous Matter

First detection of dark matter



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

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?

$\Omega_M = \rho_M / \rho_c$

Recent measurements:

$\Omega_M \sim 0.27$

$\Omega_\Lambda \sim 0.73$

$\Omega_{Lum} \sim 0.005$

~2% (Luminous)

~98% (Dark)

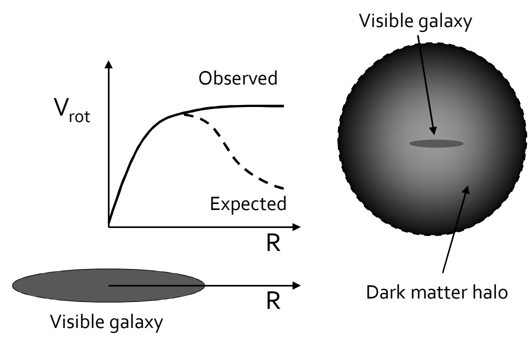
How do we know that it exists?

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

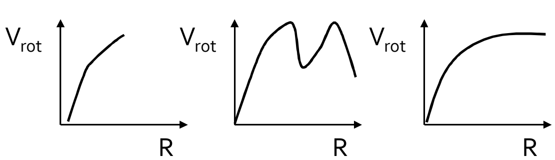
Dynamics of Galaxies I

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

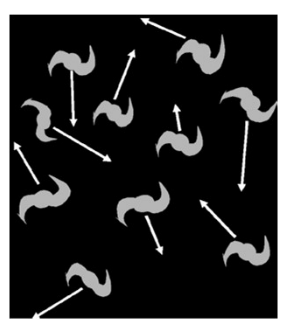
Dynamics of Galaxies II



Intermission: What do these rotation curves tell you?



Dynamics of Galaxy Clusters

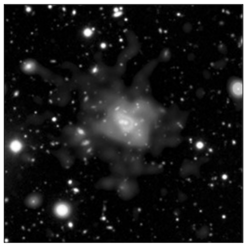


Balance between kinetic and potential energy → Virial theorem:

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

Check out Sect. 6.3.2 in Schneider's book for details

Hot Gas in Galaxy Clusters



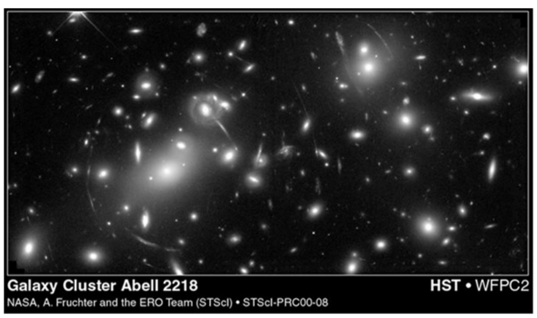
High mass required to keep the hot gas from leaving the cluster!

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

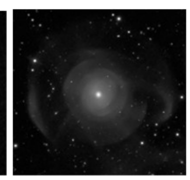
X-ray gas, T=10^7—10^8 K

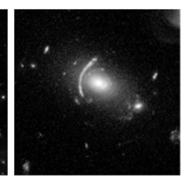
Gravitational Lensing

Gravitational Lensing II



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





Baryonic and non-baryonic matter

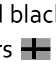
$$\left.\begin{array}{l}\Omega_M \sim 0.27 \\ \Omega_{\text{baryons}} \sim 0.04\end{array}\right\}$$

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

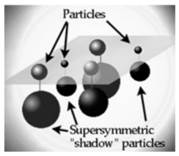
What is supersymmetry (SUSY)?

- 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

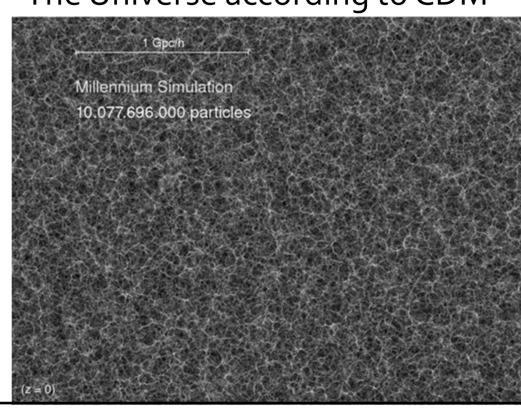
Hot and Cold Dark Matter

- 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)

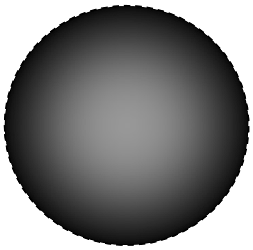
Additional Assumed CDM Properties

- 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



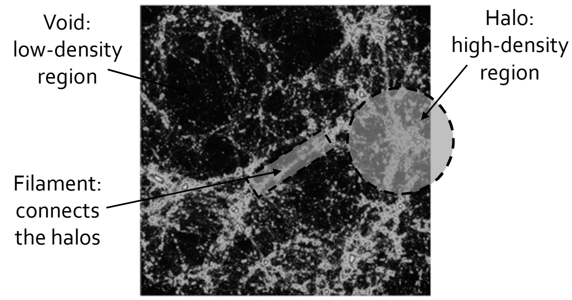
The dark matter halo



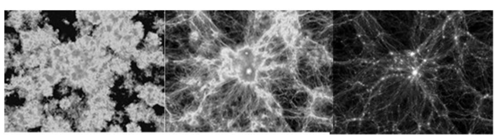
Schematic illustration

What it looks like in actual N-body simulations

Voids, halos and filaments



Intermission: What are you looking at?



Credit: Illustris Collaboration

These are frames from the Illustris simulation – showing dark matter density, gas density and gas metallicity within a cube of side ≈100 Mpc – but which frame shows what?

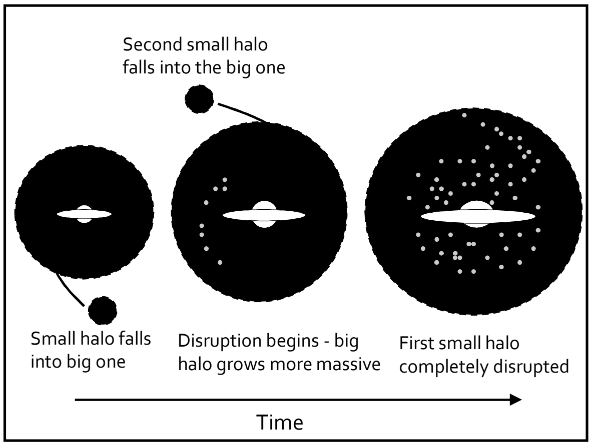
A hierarchy of dark matter halos

- 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: ???

  $M_{halo} < 10^{8}$ Msolar is a 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



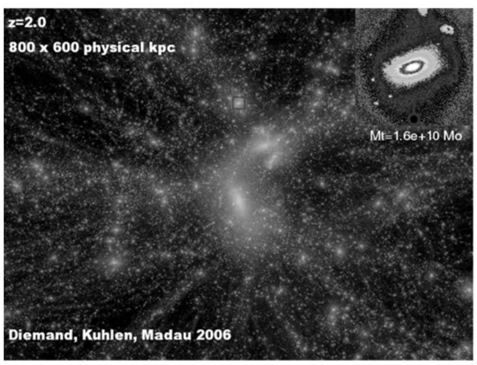
The formation of a halo

The Aquarius simulation (Springel et al. 2008)

Subhalos

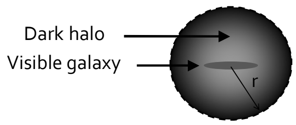
- Massive halos are assembled by the accretion of halos of lower mass
- Many accreted halos get disrupted in the tidal field of the halo they fell into, but some temporarily survive in the form of subhalos
- On average ~10% of the mass of a halo is in the form of subhalos at the current time

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)→

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

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

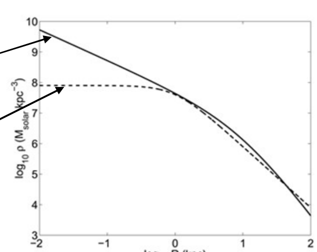
$\rho \propto r^{-3}$ at large r

NFW profile now slightly outdated, but still in active use

CDM problem I : The core/cusp issue

Predicted by dark matter-only simulations based on CDM (density cusp)

Favoured by observations of dark matter-dominated galaxies (density core)



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

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

σ(r) = constant
ρ(r) → ∞ when r → 0
M(<r) → ∞ when r → ∞
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)

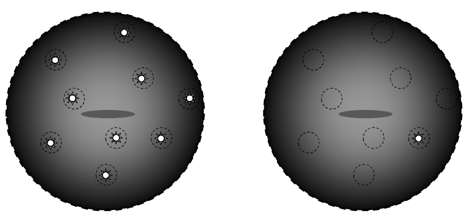
$$\rho_{\rm PIS}(r) = \frac{\rho_0}{1+(r/r_c)^2}$$

ρ(r) → ρ_0 when r → 0
M(<r) → ∞ when r → ∞
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

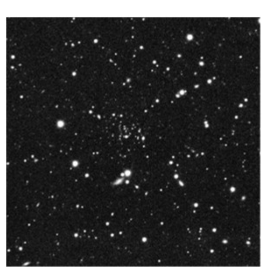
A factor of 10—100 too few satellite galaxies around the Milky Way!

CDM problem II: Missing satellites

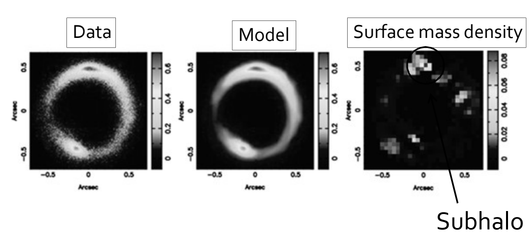
Possible solutions:

- 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

Intermission: Remember this one?

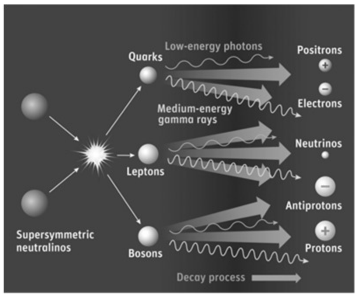


Lensing detection of subhalos



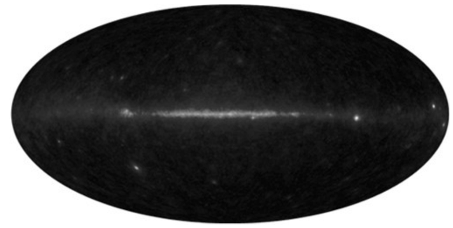
Gravitational lensing allows the detection of subhalos, even if they are completely dark – and one such object has already been detected (Vegetti et al. 2012, Nature)

WIMP annihilation



WIMPs predicted to annihilate in regions where the CDM density is high $\rightarrow$ 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 $\rightarrow$ 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)

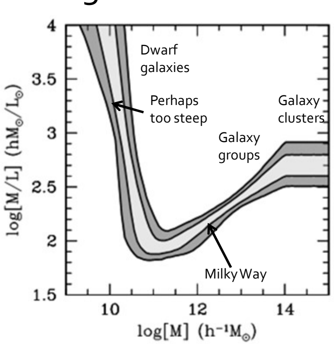
$(M/L)_{tot}$ ~100 for large galaxies

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

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

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

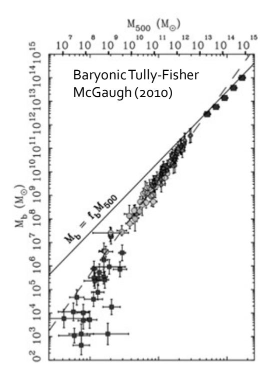
Mass-to-Light Ratios III



Model by Van den Bosch et al. (2005)

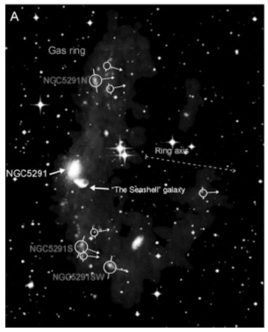
Baryon fractions

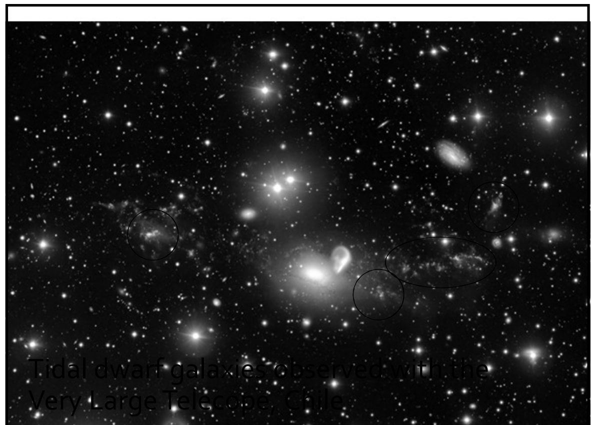
- Baryon fraction f_b below cosmic average in nearly all galaxies
- Long-standing missing-baryon problem: About 1/3 of the cosmic baryons unaccounted for at z=0
- Many of the missing baryons have recently been found in the intergalactic medium (in between halos)



Tidal dwarf galaxies

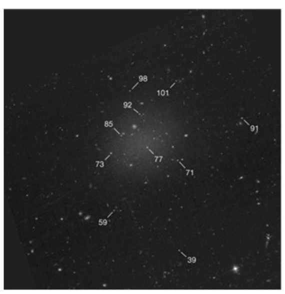
- TDGs form out of shredded disk material
- Only type of galaxy predicted and observationally confirmed to be nearly CDM-free





Tidal dwarf galaxies observed with the Very Large Telecope, Chile

Late-breaking news: An ultradiffuse galaxy without dark matter



This could be the first evidence of a second mechanism for creating galaxies without dark matter!

Nice topic for literature exercise!

Van Dokkum et al. 2018, *Nature* **555**, 629