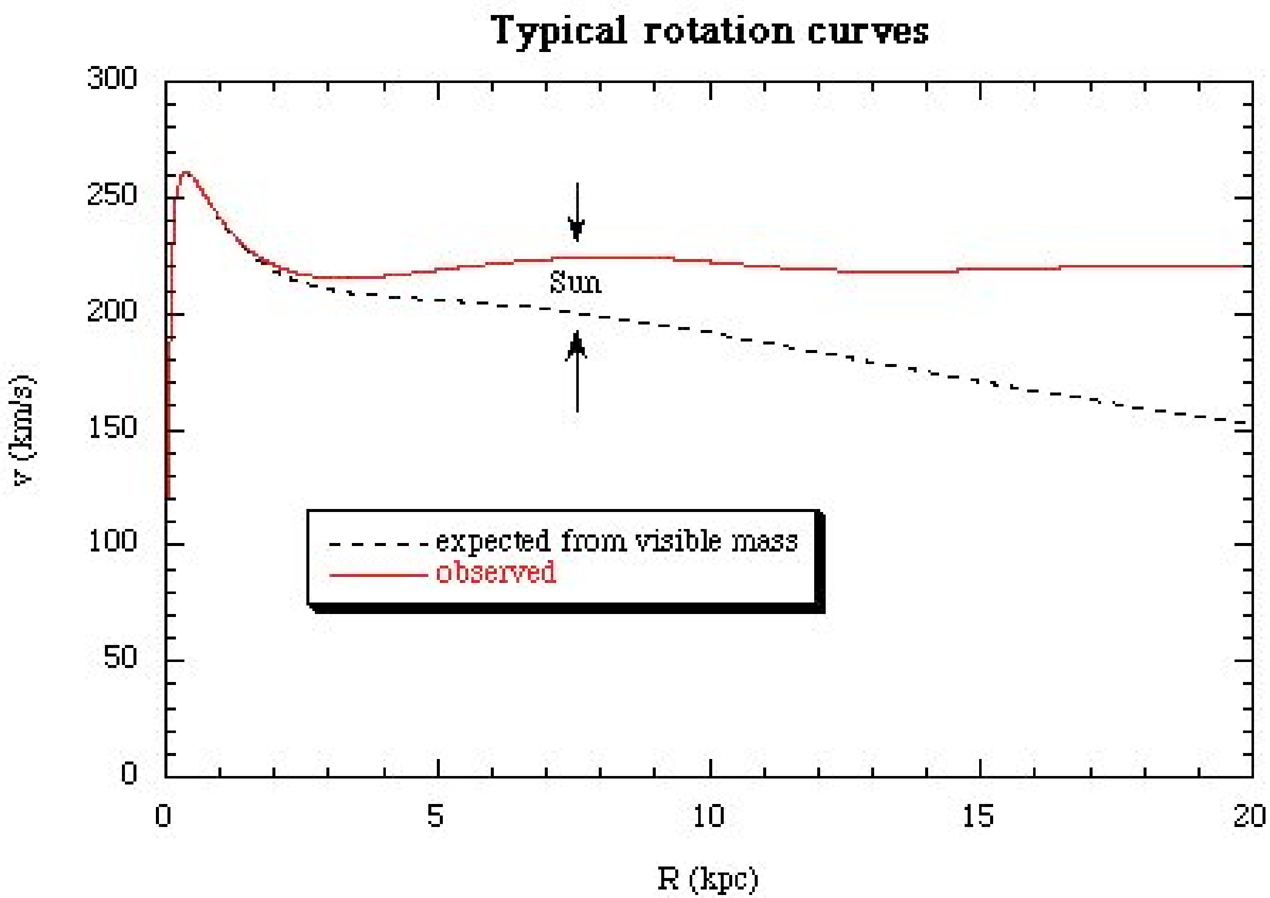
Dark Matter in Galaxies I:

Galaxy mass profile

The problem: rotation curves of disk galaxies



Properties of Dark Matter

– we can´t “see” it

– we don´t know its nature

– interact through gravity with “normal” matter

Observational tools to know the DM properties

- Disk rotation curves
- Stellar kinematics
- Gas rings
- Motions of globular clusters
- Satellite galaxies
- Hot gaseous atmospheres
- Gravitational lensing

To understand observational data ◊ simulations

Numerical Simulations

- N-body simulations ◊ simulate the evolution of DM halos in their cosmological contex

- Cosmological context ◊ CDM Model
  - Inflactionary universe dominated by a DM particle
  - Hierarchical structure formation:

    Small dense halos collapse at high z ◊ large virialized system with the galaxies we observe today

- Initial conditions
  - Smooth universe perturbed with small irregularities
  - Small irregularities ◊ Zel´dovich approx ◊ initial power spectrum
  - Only gravity ◊ they include a gravitational softening to suppres the relaxation effects due to two-body encounters

Simulation Method

More massive systems → more particles → Better resolved → numerical artifacts in mass trends

- First simulation of large periodic boxes
- Identification of equilibrium halos
- Resimulation of each halo at higher resolution ◊ Particles of halo traced back to initial conditions
- Resimulated halos have the same resolution within the virial radius

Important parameters

- Virial radius (r_{200})◊ radius of the sphere emcompassing a mean overdensity of 200 (halo radius)

  for Ω=1 approx separates virialized and infall regions
- Halo mass (M_{200})
- Scale radius (r_s)◊ scale in wich mass profile changes shape
- rms fluctuations (σ_8) ◊ determines when the simulation stops (present time)
- Caracteristic overdensity of halo (δ_c)
- Concentration ($c=r_{200} / r_s$)
- Circular velocity (V_c)

- Optical radius of a galaxy (r_{opt}) ◊ encloses 83% of total B-band luminosity (3.2 exponential disk scale)

Galaxy mass profiles

- Isothermal ◊ describes inner part of clusters very well (need a truncation)
- Hernquist model ◊ good description of elliptical galaxy photometry
- NFW (Navarro-Frenk-White)
- Moore et al.

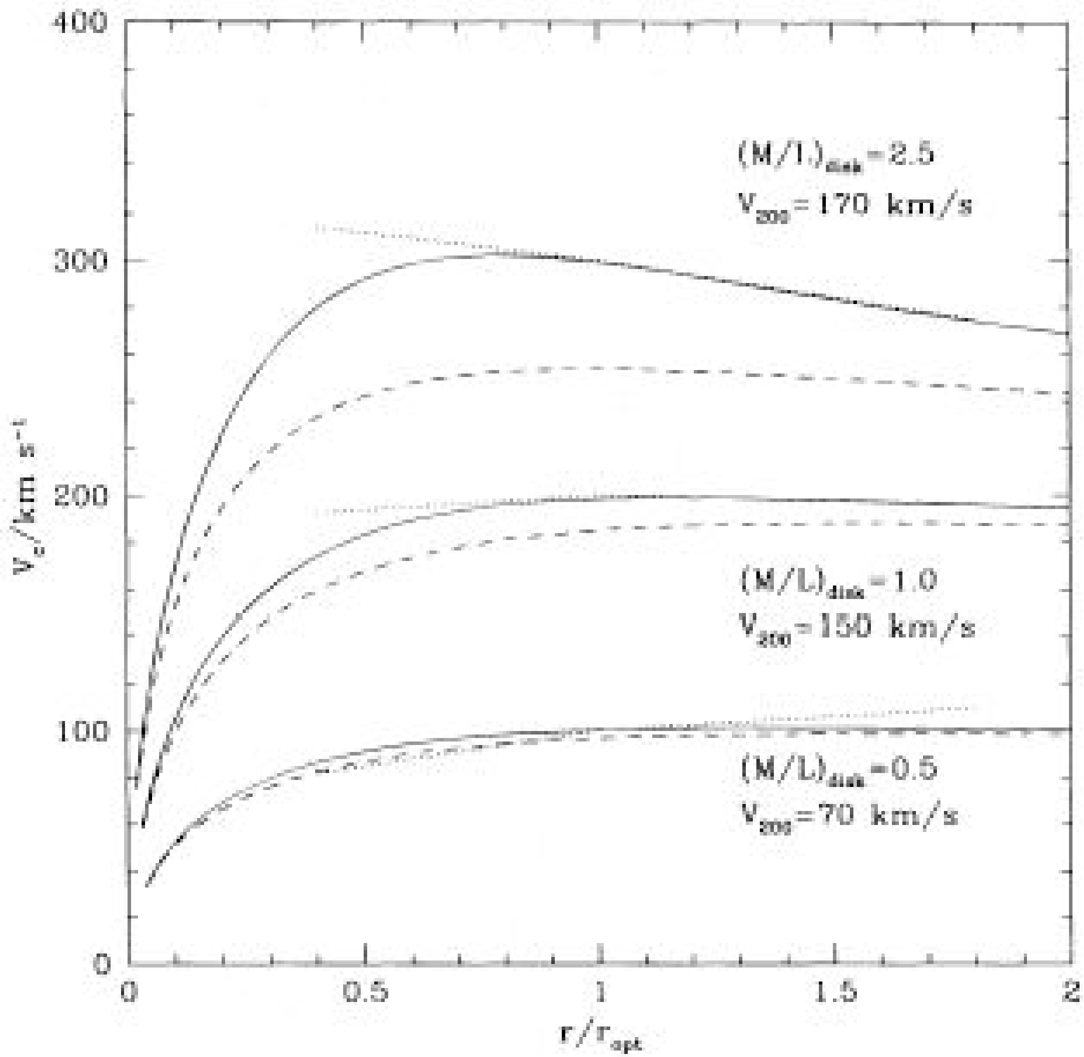
Problems

- Shapes of rotation curves
- Dynamics of binary galaxies and satellite companion
- Core properties of galaxy clusters (X-ray and gravitational lensing)
- Abundances of galactic dark halos (substructure of DM)

- Slope of the inner density distributions

Problem: Shapes of rotation curves

- Rotation velocity:
  - Less luminous galaxies: rising
  - Brighter galaxies: gently declining
- The model should exhibit 2 correlations:
  - Persic & Salucci 1995 ◊ strong correlation between r_{opt} and v_{opt}
  - Tully-Fisher relation: total B-band luminosity of a galaxy correlated with v_{opt}
- NFW assume:
  - Disk assembled slowly
  - Halo adiabatically compressed during the process



- Halo= dashed line
- Disk+halo=solid line
- Slope of rotation curve near r_{opt} = dotted line

The halo structure implied by this model has v_c significantly smaller than v_{opt} over the emiting regions

Observed rotation curves of spiral galaxies are consistent With the structure of CDM halos Provided that the assembly of the luminous component of galaxies was inefficient in low-mass halos

Problem: Dynamics of binary galaxies

- Tully-Fisher relation: $L \alpha (V_{max})^4$
  - Brighter galaxies have more rapidly rotating disks

- Asumed that max. $(V_c)_{disk} \equiv$ mean $(V_c)_{halo}$
  - expected strong correlation between luminosity of the system and the observed relative velocity diference between components in binary galaxies

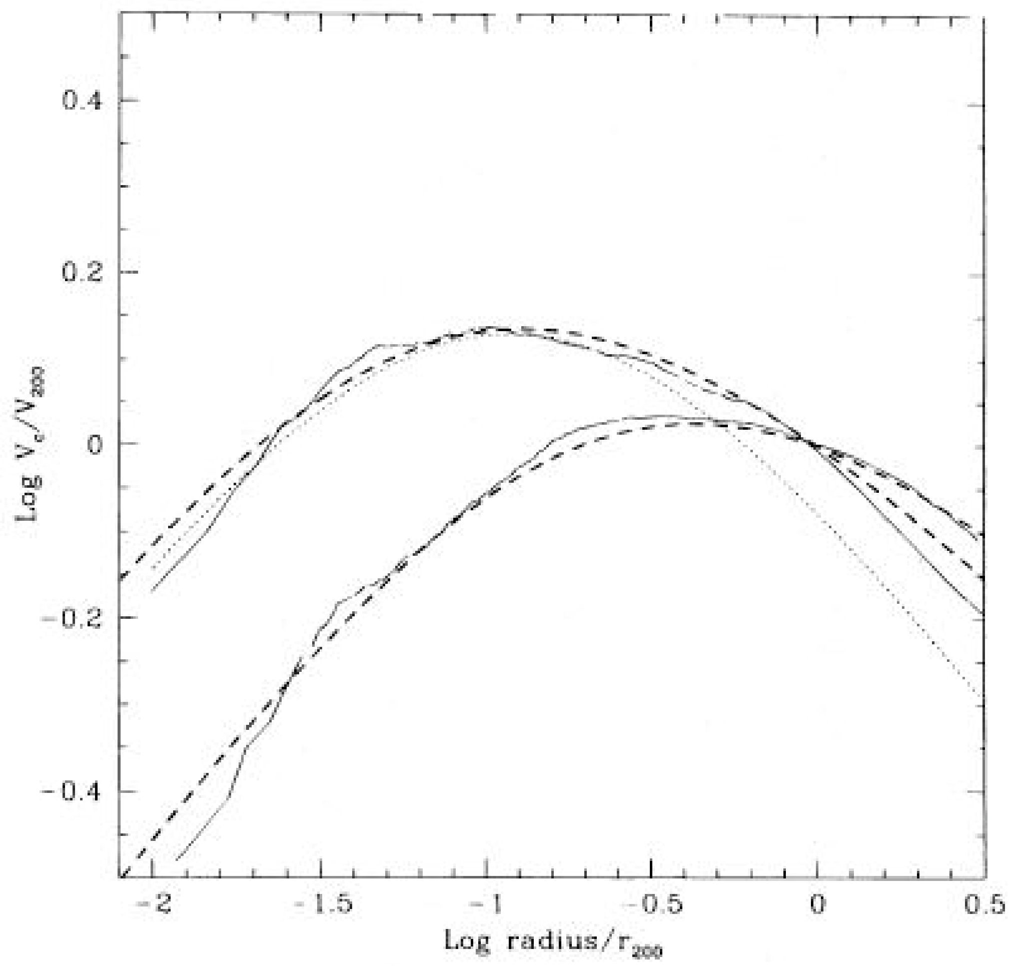
Problem ◊ This correlation is not supported by data

Solving the problem of binary galaxies

NFW 1996

- circular velocity of halos derived by simulations varies with radius ◊ the asumption breaks down
- the mean circular velocity of halos derived by their formula is almost uncorrelated with V_{opt} ◊ uncorrelated with the luminosity of galaxy ◊ agree with data

Circular velocity of halos (NFW 1996)



Dotted line=hernquist

Solid line=data

Dashed line= NFW

Hernquist and NFW profiles differ significantly at large radii perhaps because ellipticals are relatively isolated systems whereas dark halos are not

Problem: Core Properties of galaxy clusters

- X-ray observations of intracluster medium:
  - Appox by hydrostatic isothermal β-model
  - r_{core} = 100 -200 Kpc
- Giant arcs due to gravitational lensing
  - β-model for describe the lensing cluster
  - r_{core} = 20 -60 Kpc

Problem ◊ discrepancy in the size of core galaxy cluster

Solving the problem of core galaxy cluster

- If we assume that cluster halos follows the NFW profile:
  - A CDM cluster with mean velocity dispersion ~ 1000 Km/s at z=0.3 can reproduce gigant arcs
  - Detailed cooling flow models that use the potential corresponding to NFW profile rather than β-model can agree well with observations
- Conclusion: galaxy clusters are better explained with NFW profile rather than β-model

Problem: Abundance of galactic dark halos

- If we suppose 1 galaxy per halo ◊ it´s impossible to match the Tully-Fisher relation and the galactic luminosity density simultaniously :
  - If we match the TF relation ◊ galaxy luminosity density higher than observations
  - If we match luminosity density ◊ TF relation too steep

CDM cosmology predicts too much galactic size halos ◊ substructure problem

Conclusions NFW 1996

- Density profiles of CDM halos of all masses fitted by a universal profile with no free shape param. ◊ NFW profile
- Predicted structure of galaxy cluster consistent with X-ray observations and gravitational lensed arcs
- CDM halos too concentrated to be consistent with observations of rotation curves of dwarf galaxies

- Observed rotation curves of disk galaxies compatible with halo structure if mass-to-light ratio of disk increases with luminosity. ◊ Mass halo weakly correlated with luminosity ◊ explanation of why luminosity and dynamics appear uncorrelated in binary galaxies

- Bright galaxies surrounded by lower mean circular velocity halos ◊ exacerbates the problem of number of halos and galaxies

Conclusions NFW 1997

- Density profiles of DM halos have the same shape independent of:
  - Halo mass
  - Initial density fluctuations spectrum
  - Values of cosmological param

- Characteristic overdensities of halos correlated with halo mass ($\delta_c \uparrow$ when mass $\downarrow$) ◊ due to the different formation redshifts of halos of different mass (less massive systems collapse at higher redshifts)

- Characteristic density is proportional to the mean cosmic density at the time when the mass of typical nonlinear objects was some fixed small fraction of the halo mass ◊ reflects the density of the universe at the collapse time of the objects that merge to form the halo core

Problem: Slope of inner density profile

- Dwarf and LSB galaxies ◊ dominated by DM at all radii for reasonable stellar values of M/L ◊ suitable for study the properties of DM

- High-quality rotation curves of dwarf galaxies ◊ dark halo circular velocity rises almost lineary with radius over the luminous regions

  Because we have spherical symmetry ◊ halo with a well-defined core within wich the dark matter density is approx. Constant

  Problem ◊ N-body simulations agree with singular halo models

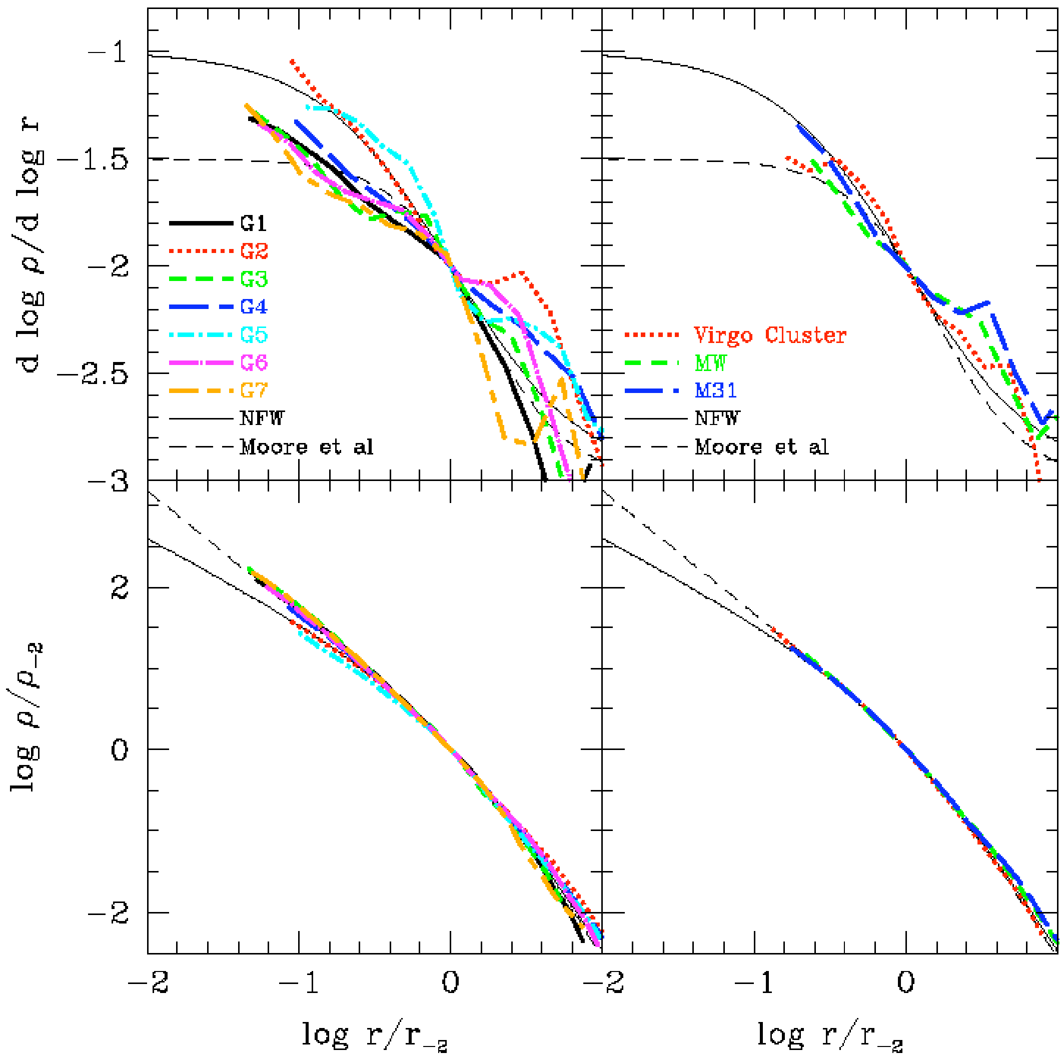
- disagreement between simulations about the expected inner slope of central power-law density distributions
  - NFW ◊ α= -1
  - Moore ◊ α=-1.5
  - Power et al. 2002 ◊ α= −1.2

- The observed HI rotation curves can often be explained by a wide range in mass models

- Swaters 2003:
  - Inner slopes with $\alpha > 1$ ruled out
  - No galaxy is consistent with α=1.5
  - Most of them are consistent with $\alpha=1$ but all of them could be equally or better explained by shallower density profiles or density constant cores

Conclusion: Inner slopes consistent with the range 0 ≤ α ≤ 1 ◊ data consistent with cuspy and cored DM halos

- Hayashi 2004:
  - Density profiles of simulated halos become progresively shallower from the virial radius inwards and show no sign of approaching a well-defined power law near the center
  - At r_{conv} density profile:
    - Steeper than NFW ($\alpha=1$)
    - shallower than More ($\alpha=1.5$)



Hayashi 2004:

no sign of
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Conclusions of Swaters 2003

- They measure the slope of the central mass distribution from :
  - Mass density distrib. implied by the rotation curve
  - Fitting mass models to the rotation curves

- 75% of galaxies consistent with ΛCDM
- 25% galaxies (predominantly barred) are incompatible with NFW . Explanation:
  - rotation curves of this galaxies could be afected by noncircular motions
  - Halos of barred galaxies intrinsically have shallower slopes

Conclusions of Hayashi 2004

- They compare circular velocity curves from simulations directly with the full measured rotation curves of LSB galaxies
- Galaxie´s shapes of rotation curves and infered central densities:
  - 70% consistent with CDM haloes
  - 20% cannot be fit by any smooth fitting function with few 3 param
  - 10% inconsistent with CDM haloes ◊ shapes of rotation curves and inferred central densities insufficiently constrained by data

- Some systems are better fit by NFW and others by M99 ◊ studies based on a single halo might reach significantly biased conclusions

- The inner structure of ΛCDM haloes is not manifiestally inconsistent with the majoriry of LSB rotation curves

- The presence of substructure is not directly responsible for the observed scatter in the shape of halo density profiles

Things to take into account

- Swaters 2003
  - All this profiles are in the context of CDM context ◊ if we use the WDM model we change the power spectrum and the density distributions of dark matter halos:
    - CDM: steep inner slopes and upper limit of $\alpha=1.2$
    - WDM: shallower slopes and $\alpha \sim 1$
  - Systematic erros on derived inner slopes from the mass density profile:
    - Beam smearing in the HI data
    - Galaxy inclination
    - Slit width
    - Seeing
    - slit aligment errors
    - Detailed spatial distribution of H_α emission
    - Noncircular motions

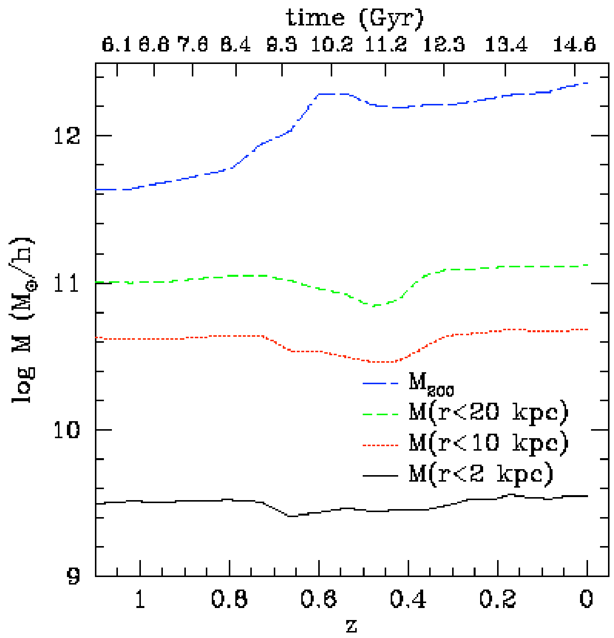
    Many can be avoid with high-resolution, two dimensional velocity field

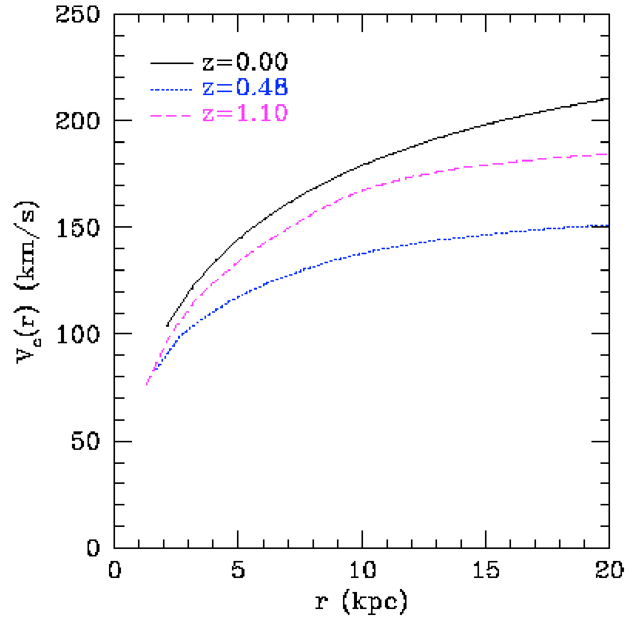
- Hayashi 2004:
  - All analysis based on the assumption that the gas rotation speed is directly proportional to the spherically averaged halo circular velocity ◊ may not be valid for real galaxies: CDM halos are triaxial, which may lead gaseosus disc to deviate systematically and significantly from simple coplanar circular orbits ◊ 3D CDM halo struture could be able to account quantitatively for the observed variety of LSB rotation curves and concentrations

  - Accretion events during the assembly of halo ◊ changes in the inner circular velocity profile ◊ increase the scatter in the shape of v_c profiles ◊ must be taken into account when comparing with observations

Accretion events

Acretion events induce changes in the central halo mass profile





Conclusions of Moore 1998

- Simulation of substructure
- Particle number and softening play a role in shaping the final density profiles
- A increase of resolution leads steepter and denser halo profiles in the center
- At virial radius the asymptotic slope of the profile is $r^{- -1.4}$

◊ problems with galaxy rotation curves