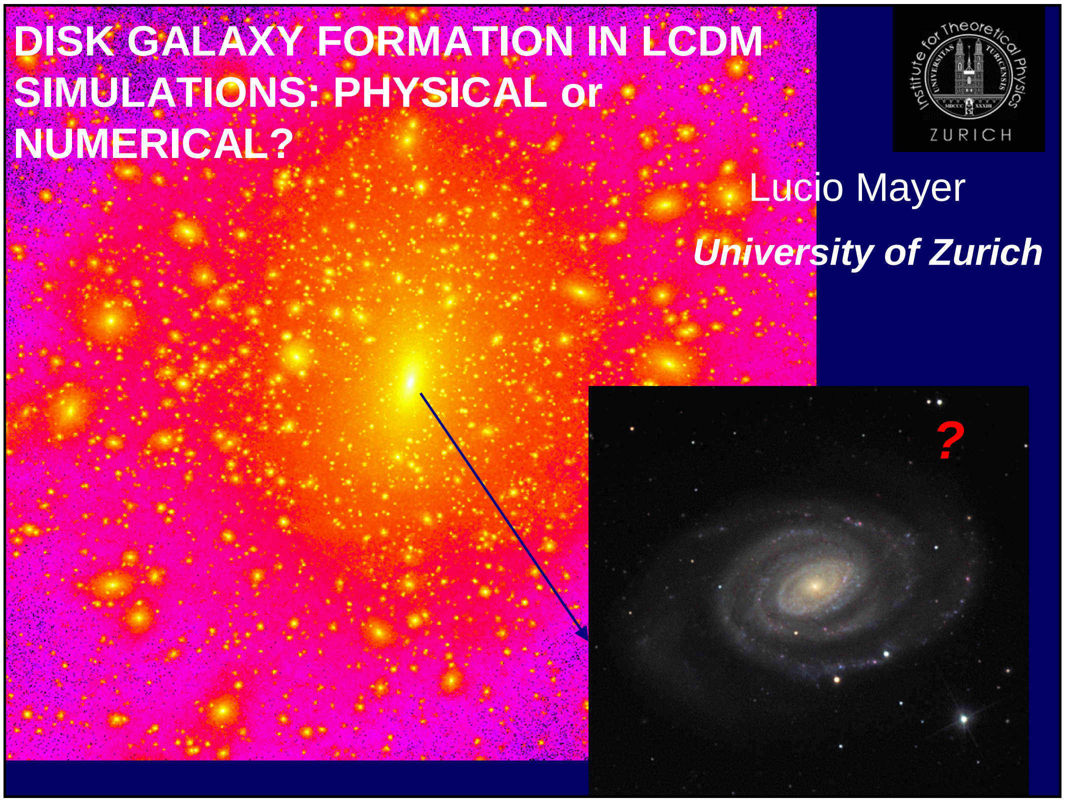
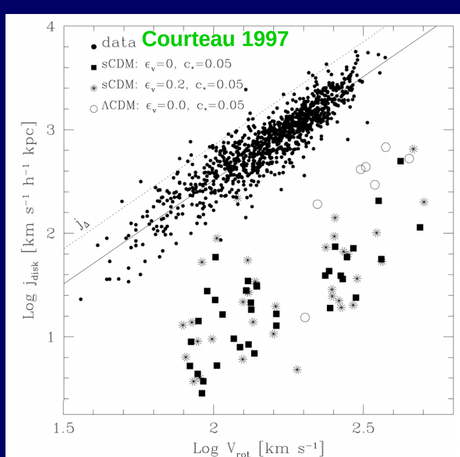
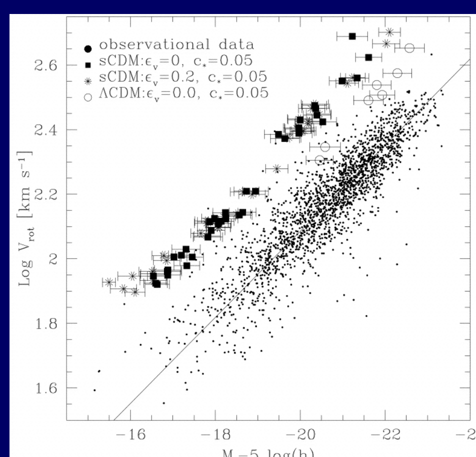


Angular Momentum Problem:scaling laws

Disks are too small at a given rotation speed (~mass)

Disks rotate too fast at a given luminosity -> mass (dark and luminous) is too concentrated

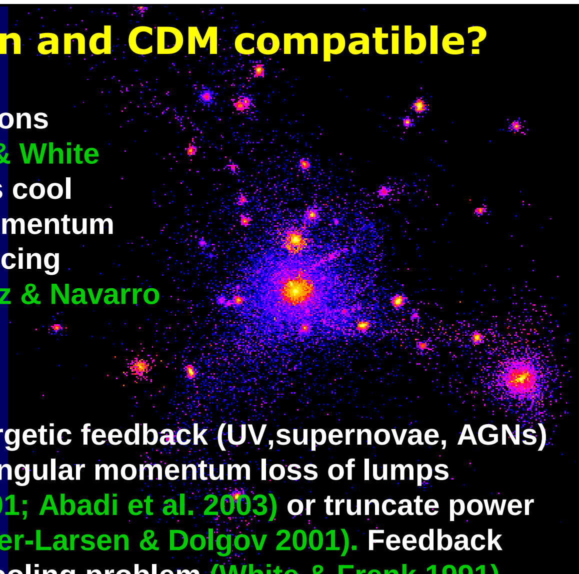




Navarro & Steinmetz 2000

Both in observations and simulations Jdisk=2Rd*Vrot, where Rd is computed by fitting an exponential profile to the stellar surface density

Are disk formation and CDM compatible?



Disks too small in CDM simulations (Navarro & Benz 1991, Navarro & White 1994) because progenitor lumps cool efficiently and lose angular momentum due to dynamical friction producing dense baryonic cores (Steinmetz & Navarro 1999,2002).

"Physical" solution: **strong energetic feedback (UV,supernovae, AGNs) to keep gas hotter and reduce angular momentum loss of lumps (Thacker & Couchman 2000, 2001; Abadi et al. 2003) or truncate power spectrum of dark matter (Sommer-Larsen & Dolgov 2001). Feedback already required to avoid overcooling problem (White & Frenk 1991).**

But how about numerical resolution? Individual galaxy objects resolved by only tens of thousands DM and SPH particles and force resolution > 1 kpc, not enough to really resolve disks!

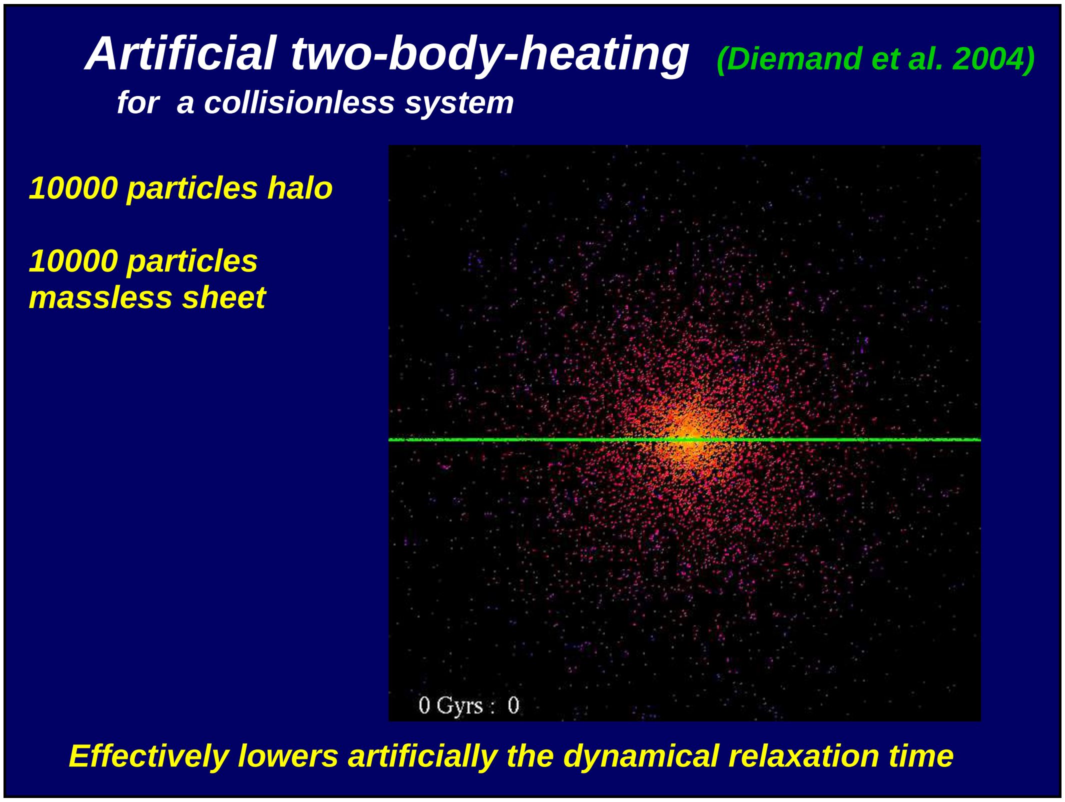
Can we trust current SPH galaxy formation simulations?
Several numerical effects *(all dependent on resolution)* can still affect disk formation even in cosmo runs

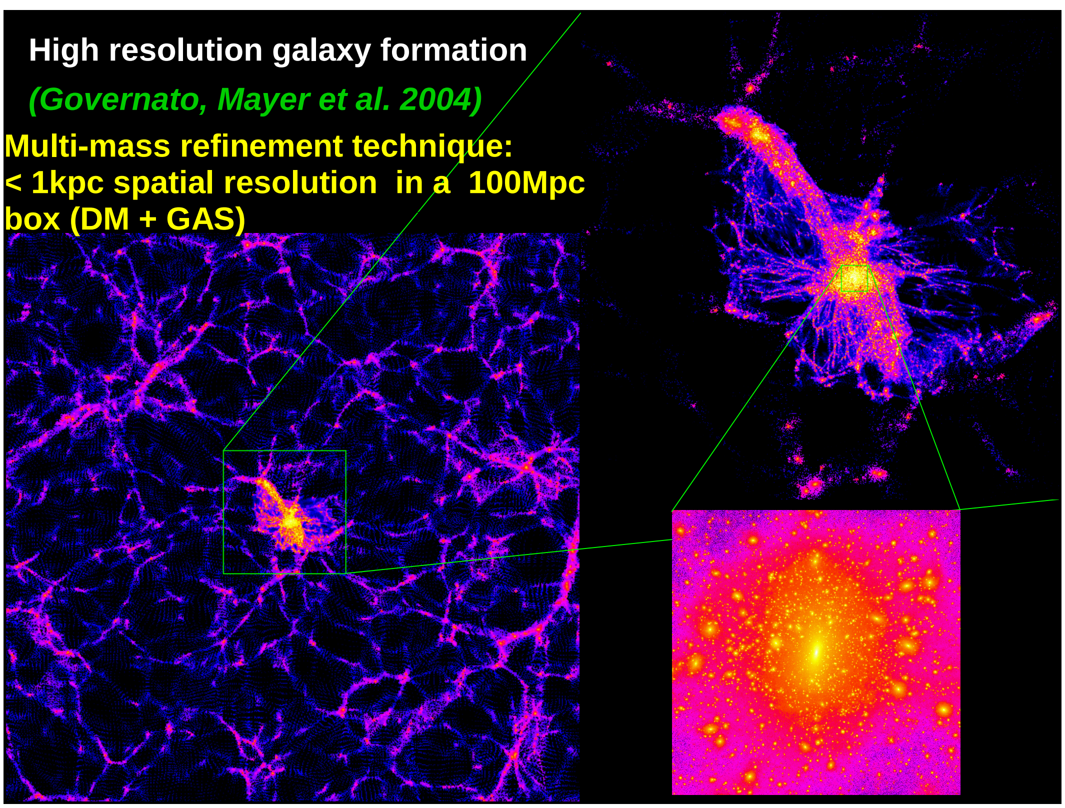
-**Artificial two body heating (Moore et al. 1996, Steinmetz & White 1997) ---> changes kinetic energy of all particles + thermal energy of the gas. "Cold" sheets can become "hot" spheroids**

- **artificial viscosity ---> needed in SPH to resolve shocks and reduce numerical noise in general, but induces artificial losses of angular momentum of the gas component (Thacker et al. 2000)**

-**spurious hydro torques -→ standard SPH does not solve for the multi-phase structure of the ISM, artificial pressure gradients can arise at the interface between a cold disk and surrounding hot gas and transport J (Okamoto et al. 2003)**

-artificial suppression/enhancement of grav. instabilities in disks noise due to particle representation triggers non-axisymmetric modes (e.g. bars), grav. softening suppresses physical modes.


Artificial two-body-heating
(Diemand et al. 2004)
for a collisionless system
10000 particles halo
10000 particles massless sheet
0 Gyrs : 0
Effectively lowers artificially the dynamical relaxation time


High resolution galaxy formation
(Governato, Mayer et al. 2004)
Multi-mass refinement technique:
< 1kpc spatial resolution in a 100Mpc box (DM + GAS)

Cosmology and Hydrodyamics with Gasoline

(Stadel 2001; Wadsley, Stadel & Quinn 2004)

-Conspirators:

James Wadsley	McMaster University
Joachim Stadel	Univ. of Zurich
Thomas Quinn	Univ. of Washington
Fabio Governato	Univ. of Washington
Tobias Kaufmann	Univ. of Zurich
Ben Moore	Univ. of Zurich
Jeff Gardner	Univ. of Pittsburgh
Beth Willmann	NYU
George Lake	Washington State U. → Zurich

Multi Platform, Massively Parallel treecode + SPH, multi stepping, cooling, UV background, Star Formation, SN feedback . Santa Barbara tested...

Physics included

- **Compton and radiative (atomic) cooling for a gas of primordial composition**

- **Star formation (Katz 1992) – gas particles spawn stars with Miller-Scalo stellar mass function in cold and dense enough regions with convergent flow and with tcool or tdyn < sim. timestep**

- **Explosions of supernovae type I and II - *a fraction of the energy is transferred to the gas only as thermal energy (thermal feedback) --> this is the 'mildest' among the possible recipes for feedback because gas quickly cools down* (see Springel & Hernquist 2002; Thacker & Couchman 2001).**

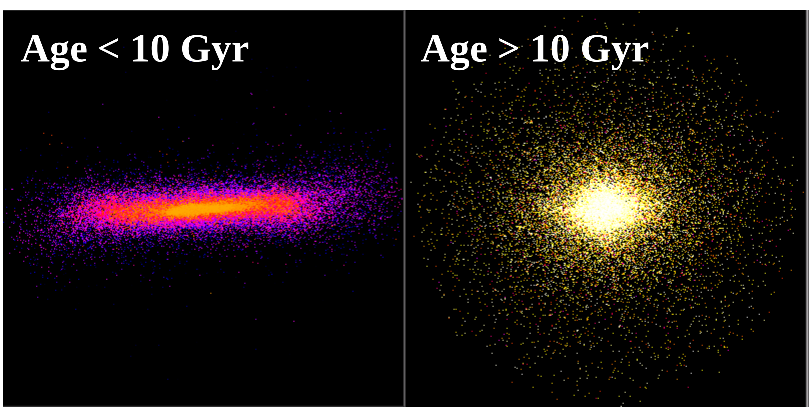
- **Heating by a uniform cosmic UV background – kicks in at z = 6 (Haardt & Madau 1999).**

The formation of a large disk galaxy in a LCDM Universe

Red: stars
Blue: gas

Virial Mass 2.9e12Mo
Virial Radius 375Kpc
Ngas (R < Rvir) ~ 200.000
Ndark (R < Rvir) ~ 100.000
Spin Parameter $\lambda = 0.035$
Vvir 185 Km/sec
C=13.6 (Mean: 13.2)
Formation time z = 0.75
(> 50% of z=0 mass)
Last major merger z=2.5

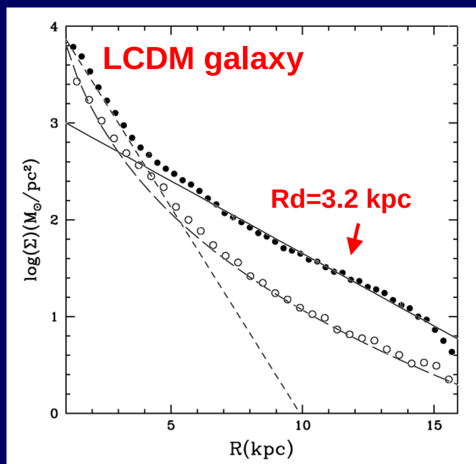
The LCDM galaxy at z=0

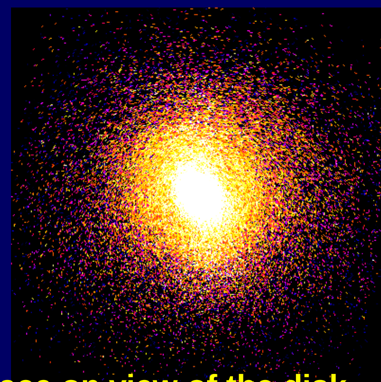


Disk (+ bar)   Bulge + Stellar Halo

Stellar surface density profile at z=0

Separate fit for old component (Age > 10 Gyr, open dots) and young component (Age < 10 Gyr, filled dots)



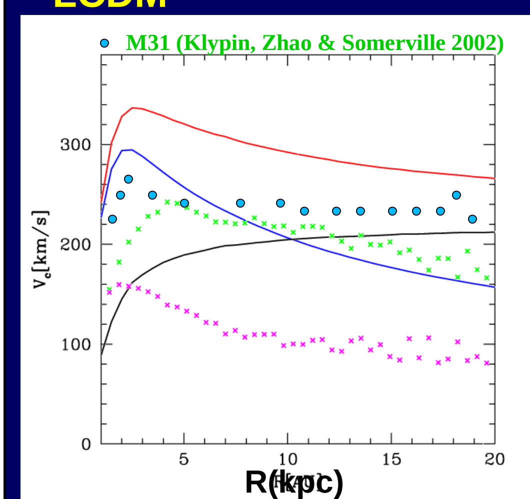


Face on view of the disk at z=0 showing the "fat" bar

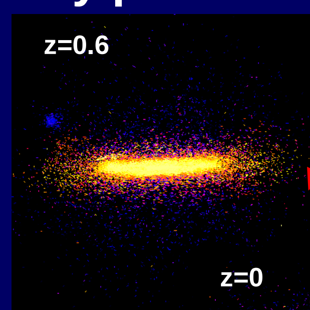
Old component is fit by a de Vaucouleurs profile, young component (including bar) by a double exponential. Disks with bars or buckled bars are typically well fit by exponentials (e.g. Combes & Sanders 1991; Mayer & Wadsley 2004) "Photometric" B/D is 0.35 for LCDM galaxy.

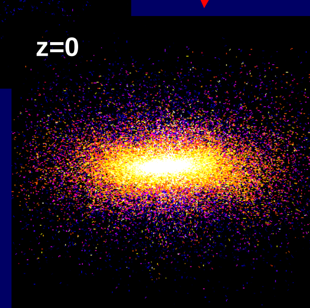
Circular velocity profile

LCDM



Disk edge-on





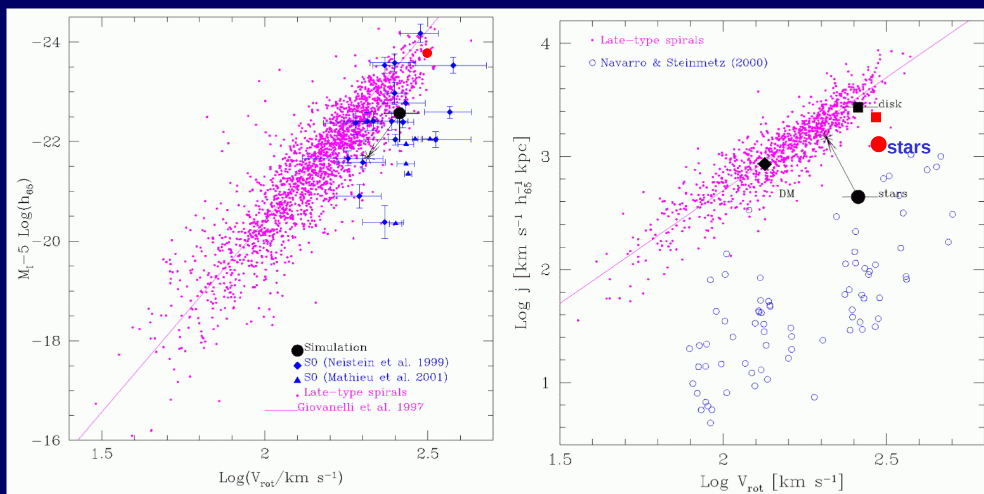
Red=total, black=dark, blue=stars, green=stars rotation, magenta=stars disp.

- **Curve steeper than that of e.g. M31 at the center due to low angular momentum spheroid (this happens also with stronger feedback in Abadi et al. 2003).**
- **LCDM disk kin. hot due to heating by satellites (numerical heating?**

Angular momentum; no more carastrophe

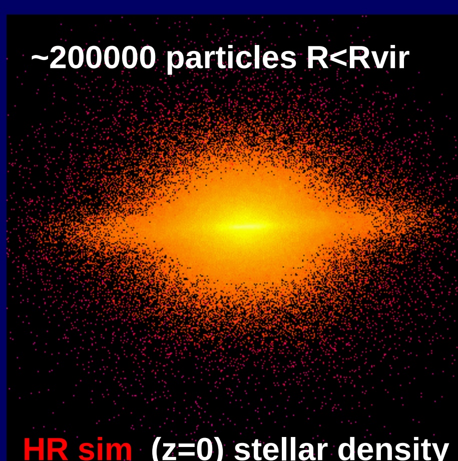
Both "our" LCDM galaxy and that of Abadi et al. 2003 have been selected based on a quiet merging history.

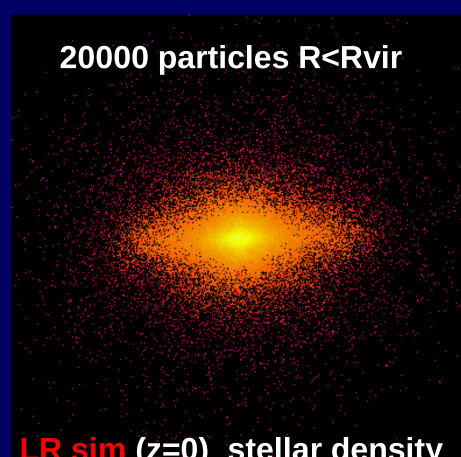
We have 5 times more resolution, they have stronger (kinetic) supernovae feedback.



We managed to form something like the Sombrero galaxy (S0/Sa type)

(see Governato, Mayer et al. 2004 for details)





We certainly gained by increasing N, but how can we measure the numerical reliability of the simulations? Can we form a bulgeless galaxy?

COSMOLOGICAL HYDRO SIMULATIONS TOO COMPLEX
HARD TO PIN DOWN PHYSICAL vs. NUMERICAL EFFECTS

NEED TO RESORT TO SIMPLER NUMERICAL EXPERIMENTS

-can be more controlled

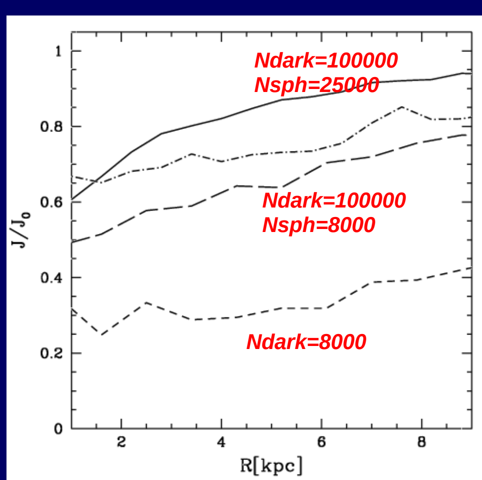
-can allow resolution studies at much larger N

EXAMPLES:

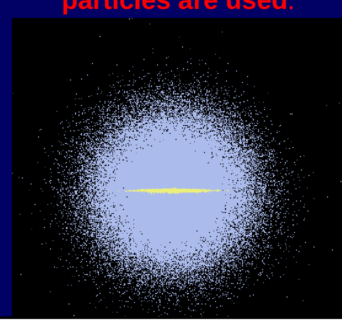
1- formation of an ISOLATED disk galaxy within a CDM halo from smooth gas accretion (no lumps) → (Kaufmann, Mayer, Moore & Stadel 2004 + in prep.)

2- study the evolution of pre-defined models of disk galaxies in LCDM halos (Mayer & Wadsley 2004; Debattista, Carollo, Mayer & Moore 2004; Debattista, Mayer et al. 2004; Mayer, Debattista et al., in prep.)

Two-body heating from dark particles: tests with isolated galaxy models



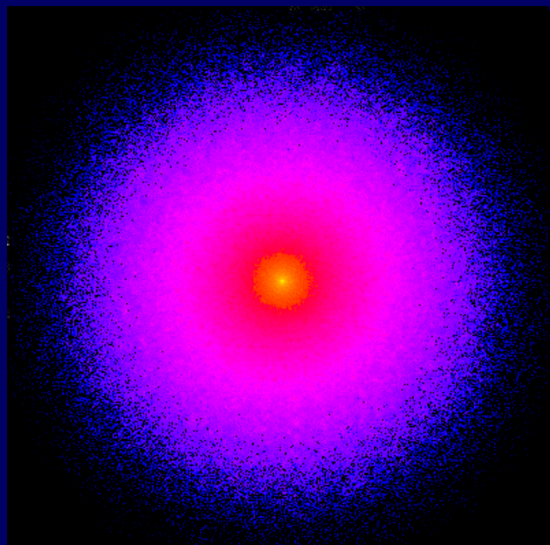
N-Body+SPH models reproduce the structure of LCDM galaxy at z=0.6, when most of the stellar disk mass is in place.
Vary Ndark, Ngas, Nstar and evolve for 6 Gyr
All go bar unstable and a disk remains only if at least 100.000 dark particles are used.



Above: decrease of J(baryons) From z=0.6 to z=0

“Isolated” disk formation

Tobias Kaufmann, Lucio Mayer, Ben Moore, Joachim Stadel (2004 + in prep.)



Dark matter halo with gas

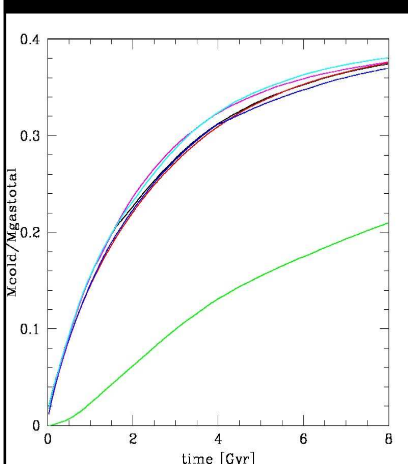
Start from NFW halo with an embedded rotating hot gaseous halo in hydrostatic equilibrium.

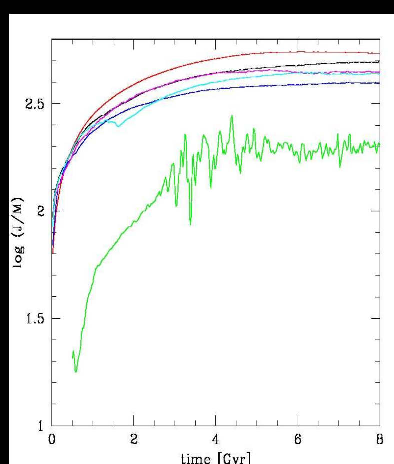
Halo virial parameters, spin and angular momentum profile motivated by LCDM cosmological simulations (Mo et al. 1998; Bullock et al. 2000)

Standard cooling function for primordial mixture of H and He (no H2) temperature floor (no UV heating or sup. feedback)

Disk mass and angular momentum convergence

MW-sized model (Vvir ~ 160 km/s, c=10, fb=0.1,λ=0.045)





green LR
100000 dm+
20000 SPH

black IR
100000 dm+SPH

red HR
1e6 dm + 5e5
SPH

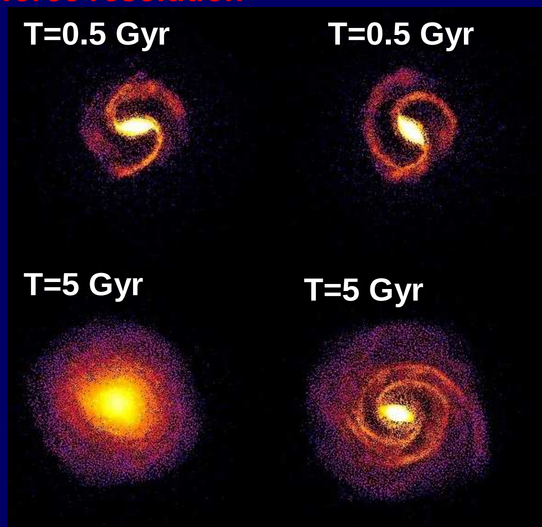
For convergence in mass, IR is sufficient, almost suff. for angular momentum.

Gas particles in a sphere of initial radius=80kpc are followed. “Cold” particles are at T ~ Tfloor and end up in the disk. At IR and HR growth of cold mass roughly consistent with semi-analytical model by Van den Bosch (2001)

Bar formation and force resolution

Simulations with same mass resolution Nsph, Ndm = (1e5, 1e5) but different force resolution

soft=2 kpc

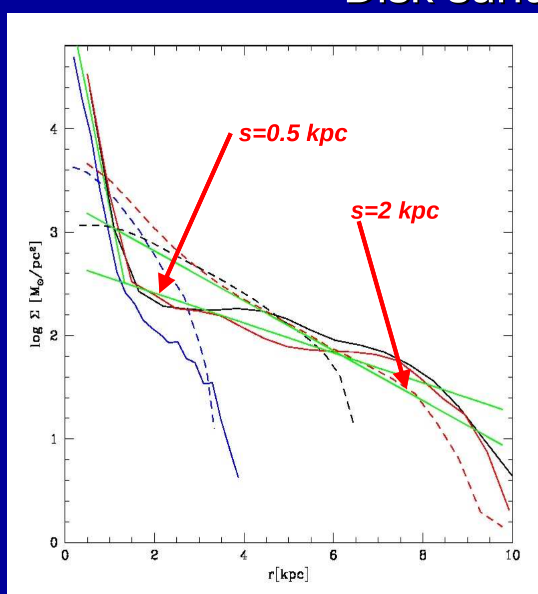


soft=0.5 kpc

Boxes=30 kpc

Long lived bars only when gravitational softening < ½ bar length at formation (cfr. Romeo 1994; Bate & Burkert 1997)

Disk surface densities



Solid lines: softening = 0.5 kpc

Dashed lines: softening = 2 kpc

Both softening, resolution, dynamics (bar formation) play a role in altering the final mass distribution

The presence of a bar increases the scale-length of the outer disk by a factor of 2 (already Hohl 1971). Important because this is the scale length we measure for early type spirals! (not include in any SAM)

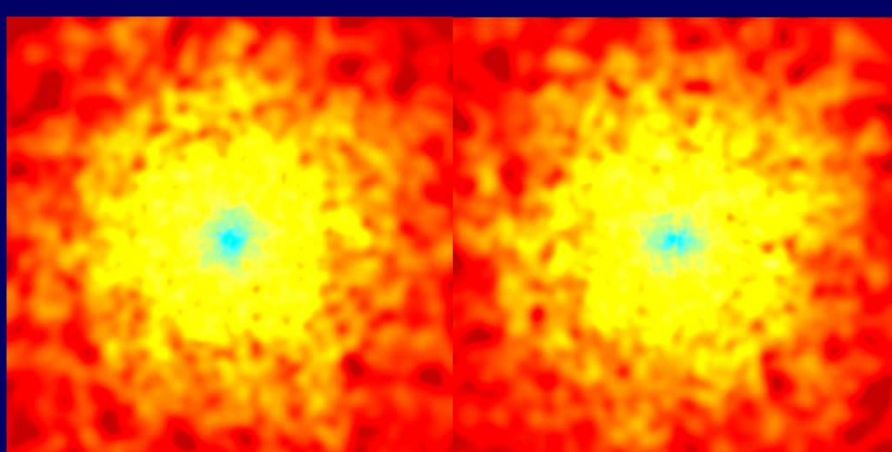
A model stable to bar formation: can we reproduce M33?

NFW Dark matter halo, Mvirial ~5e11Msolar,
baryon fraction ~ 6%
concentration c = 6.2, spin parameter lambda ~ 0.1
Halo parameters give initial slowly rising rotation curve as in M33 and most late-type spirals. High spin and low baryon fraction should yield subdominant disk stable to bar formation (Van den Bosch 2001; Mo et al. 1998)

Highest resolution model uses shells with decreasing dm particle mass towards the center:
1.1e6 dark particles **(~equivalent to 1e7 dm particles)** + 5e5 gas particles
Mass resolution < 1e5 Msolar, softening 250pc.

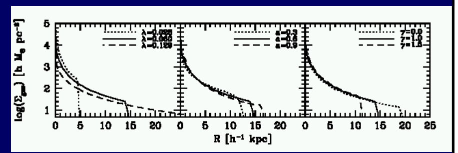
M33 model: no bar, dense nucleus

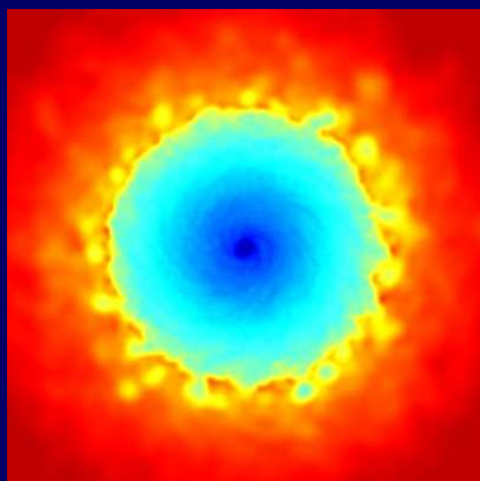
Shell model for dark matter with 1.1M dark/500k gas:
Mass resolution better than 1e5 Msolar, softening 250pc.

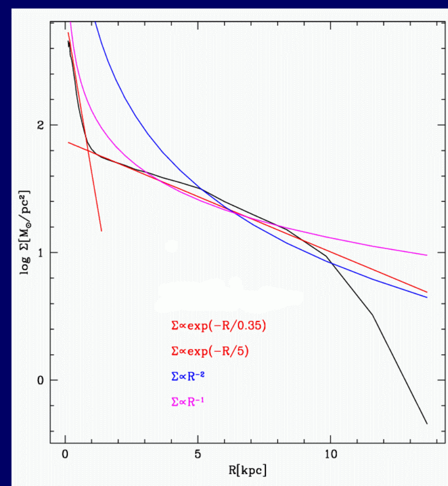


gasdensity face on **gasdensity edge on**

Van den Bosch (2001) points out a new problem for disk formation in CDM models: exponential disks cannot be obtained with Jgas(r) ~ Jhalo(r) because the gas collapses too much in a cuspy halo → a power law disk profile is produced







LCDM simulations with feedback

With Fabio Governato (UW) Greg Stinson (UW) Octavio Valenzuala (UW), Alyson Brooks (UW), Beth Willman (NYU) and James Wadsley (McMaster)

Use SF+SN feedback algorithm in LCDM simulations *to study the ab initio formation of three disk galaxies over a range of masses:*

3e11 Mo (small galaxy), 1e12 Mo **(Milky Way like)**, 3e12 Mo **(giant spiral)**

Spatial resolution: 0.3-0.6kpc
Mass resolution: 150.000+150.000 DM+gas particles within virial radius .
Simulations carried to z=0.

Halos picked with: a quiet merging history (last major merger at z>2) typical formation time for their halos: ~ z=0.9-0.7

Conclusions

-Current state of the art cosmological SPH simulations produce disks with nearly the right size but central spheroid always too massive → lowers the global angular momentum of the galaxy below that of typical spirals and steepens the rotation curve too much.

-Quiescent merger history with late smooth infall of high angular momentum gas crucial for disk formation.

-Tests show > 100.000 dm halo particles needed to avoid numerical loss of angular momentum due to two-body heating. Similar resolution needed in SPH part to avoid artificial losses from other sources. In cosmo simulations resolution much lower in early progenitors making up the old spheroid.

-Disk instabilities (e.g. bars) shape mass distribution/disk scale lengths, resolution in cosmo runs still insufficient to follow them

-Early (z>6) strong feedback/heating important for getting the right number of satellites and can reduce mass of stellar halo/spheroid (under investigation..) but resolution more important for disk size.

Star formation + feedback recipe

- **Star Formation Efficiency:** ***fraction of gas turned into stars***
- **Efficiency of SN Winds:** ***fraction of energy of supernovae explosion that goes into the wind***
- **Turbulence of the IGM:** ***"entrainment factor" i.e. amount of gas affected by the wind + timescale for decay of turbulence (Silk 2003)***

-Gas is eligible to form stars when cold, dense and Jeans unstable

-Gas receives energy from nearby SNII and is not allowed to radiate energy for 20-30 Myr (Thacker & Couchman 2000).

-Gas is metal enriched by SN I&II

-Miller Scalo IMF assumed.

Algorithms tested with compound galaxy models (see also Springel et al. 2002, 2004) of a Milky Way and a dwarf galaxy

-SFR as from SDSS on a wide mass range
-Reproduce Schmidt Law in MW model
-Stellar Rz/Rdisk ratio
-Volume ratio Cold Gas/Hot gas (Porosity)
-Cold Gas turbulence

Isolated galaxies with “best” Star Formation parameters.
SF efficiency 0.05/Tdyn
SN efficiency = 0.6 * 10^51 erg
entrainment factor ~ 1000 (ratio of SNs mass/mass ISM)

Gas Rich Dwarf Galaxy Vc ~70Km/sec

Gas=white

Milky Way As Klypin, Zhao & Somerville 2001, Vc ~ 160 km/s

Gas=red
Stars=white

SFR
Stellar Rz/Rdisk ~ 0.3
Volume ratio Cold Gas/Hot gas ~ 0.5-1 within stellar disk
Cold Gas turbulence ~ 20Km/sec

The formation of a large disk galaxy in a LCDM model.II

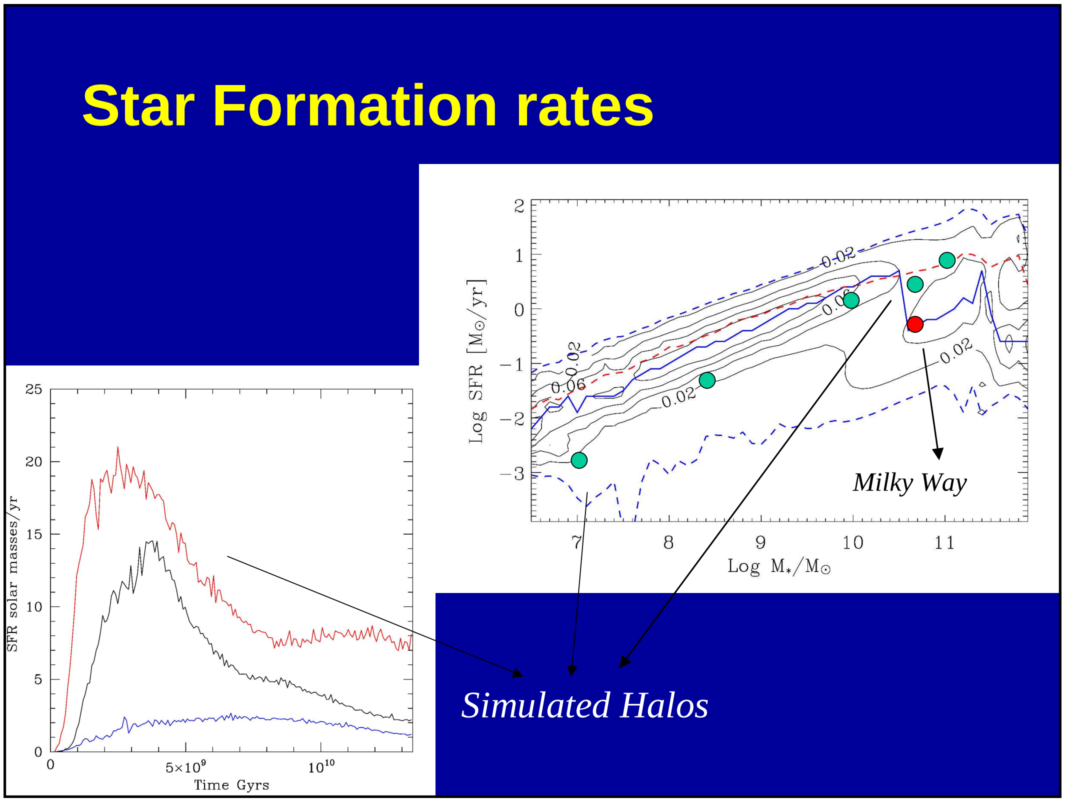
Red: stars
Blue: gas

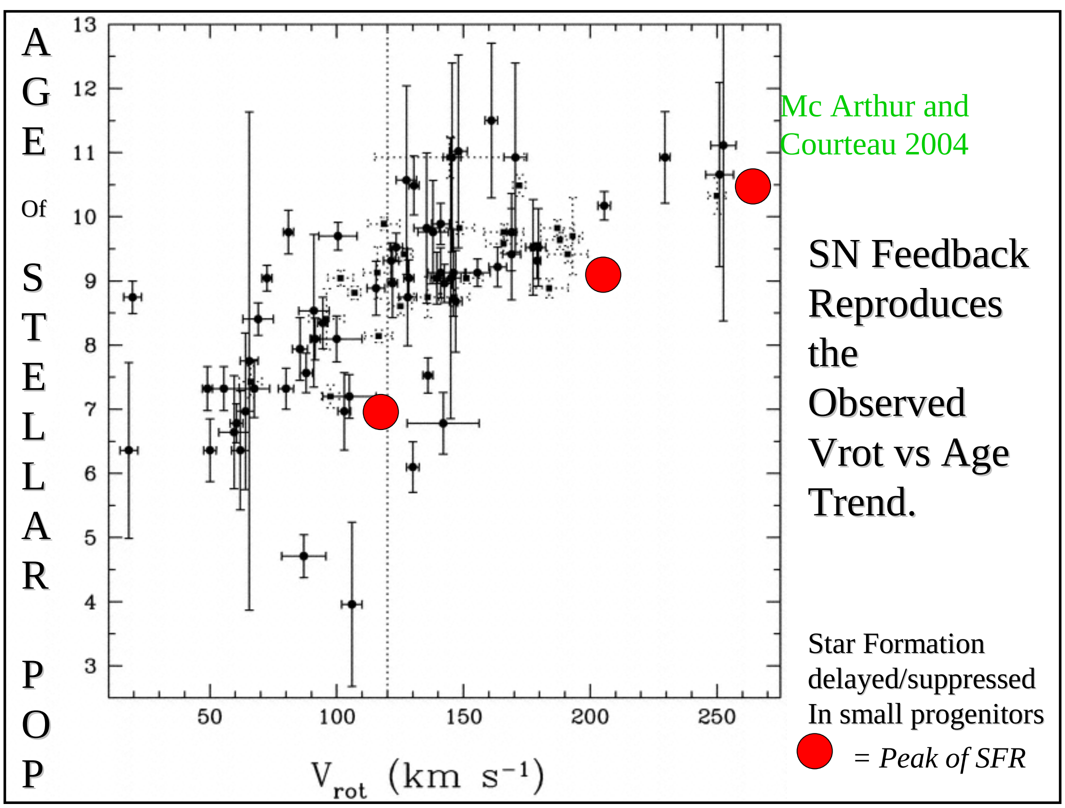
Total Mass 3e12 Msol
Spin Parameter = 0.035
Vrot Max 270 Km/sec
Formation time z = 0.75
Last major merger z=2.5
Frame size ~ 200 Kpc

No Feedback.

UV+SN Feedback

With feedback ~ same disk size, but only a few luminous satellites


Star Formation rates
SFR solar masses/yr
Time Gyrs
Log SFR [M⊙/yr]
Log M*/M⊙
Milky Way
Simulated Halos


AGE Of STELLAR POP
Vrot (km s−1)
Mc Arthur and Courteau 2004
SN Feedback Reproduces the Observed Vrot vs Age Trend.
Star Formation delayed/suppressed In small progenitors
= Peak of SFR