The formation and evolution of galaxies in the ΛCDM model

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Outline

-Short review: physics of galaxy formation in the cold dark matter model (SKA excellent probe)

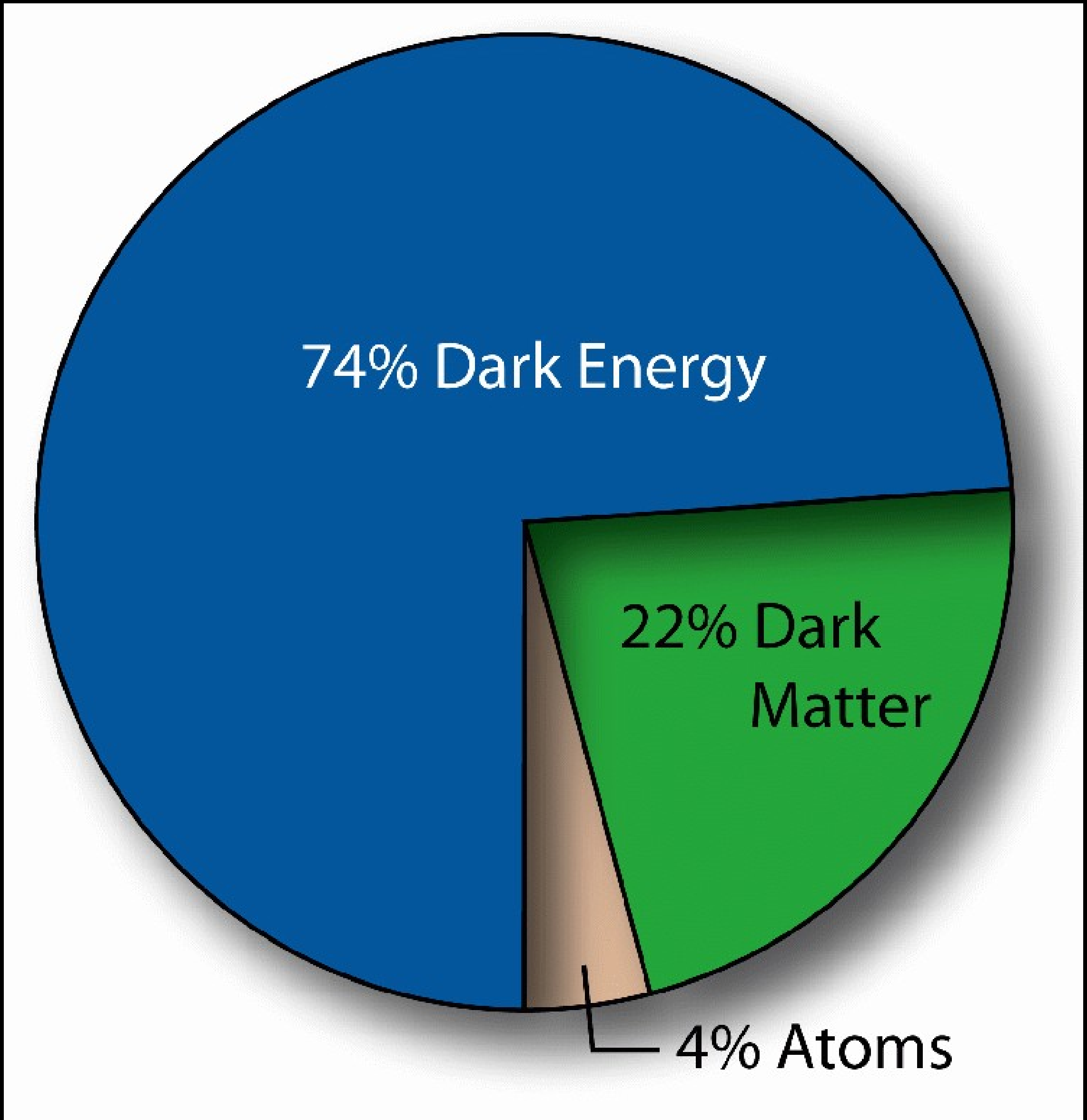
-Simple models of disk galaxy formation

-Cosmological simulations of galaxy formation

- Long standing problems: the angular momentum of disks
- New successes ---→ formation of realistic disk galaxies
- Cold gas as a tracer of galaxy formation --- synergy between simulations and SKA

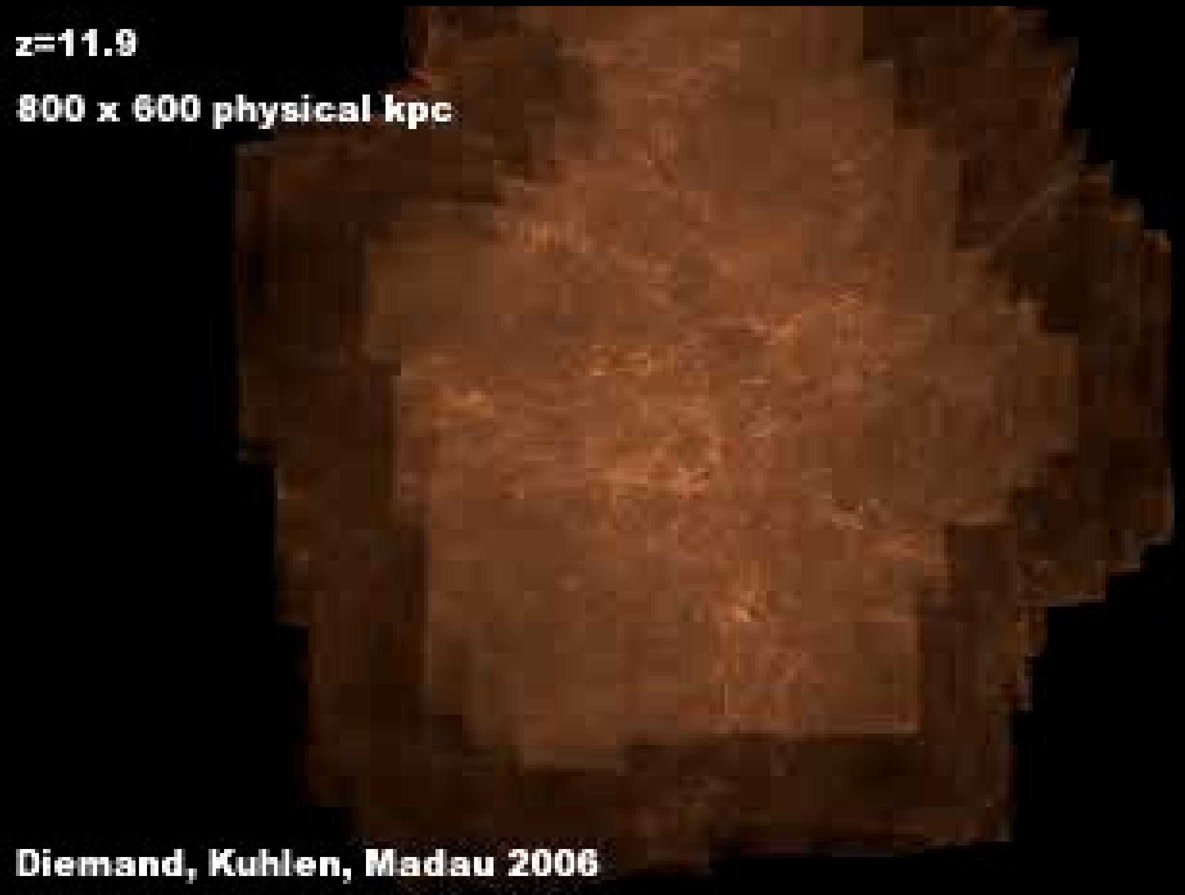
Evolution of HI disks of spiral galaxies, gas accretion, galaxy interactions

The current cosmological paradigm: the ΛCDM model



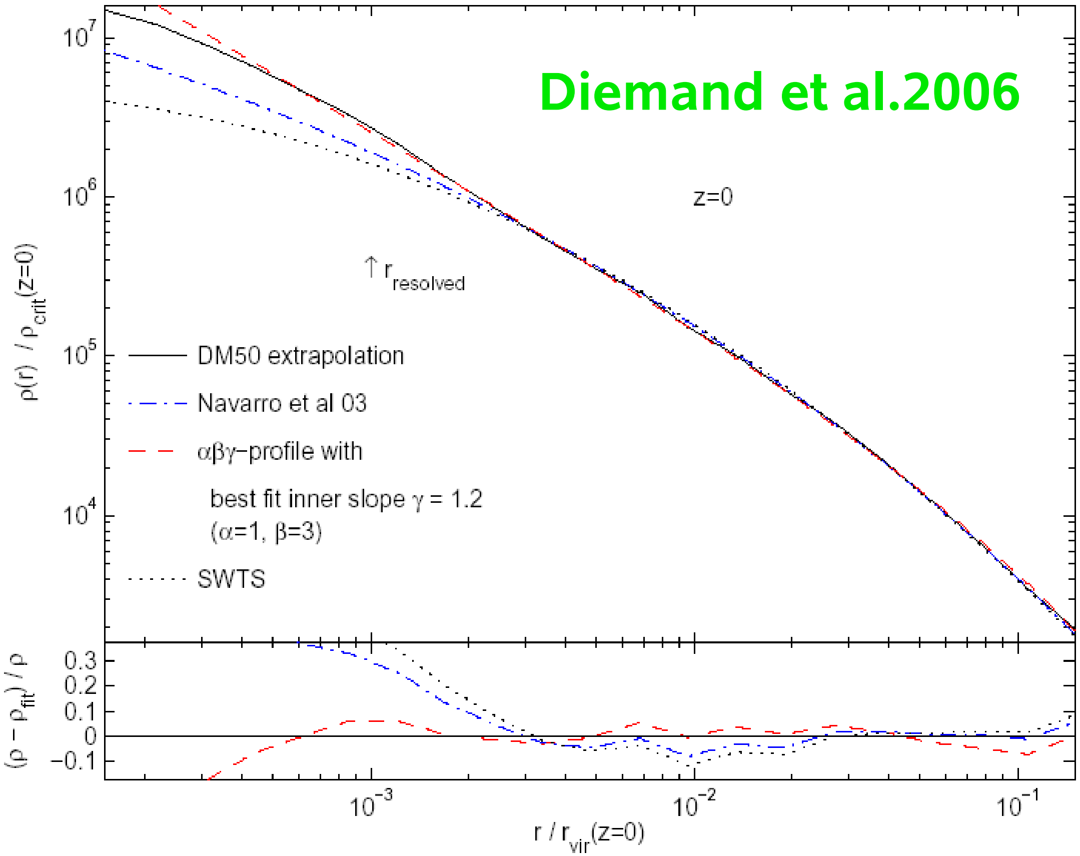
Cold Dark Matter (CDM) = particles interact via gravity, (e.g WIMPS), negligible thermal velocity, collisionless physics

Bottom-up formation of Milky Way halo in ΛCDM model



Via Lactea - largest simulation of galaxy halo (Diemand et al. 2007)
300 million particles with our parallel treecode PKDGRAV

Structure of dark matter halos



From spherical collapse model (Gunn & Gott 1972): halo virialized out to the radius r_{200} where $\rho=200\rho_{crit}$

Virial radius $r_{200} = \dfrac{V_c}{10H(z)}$

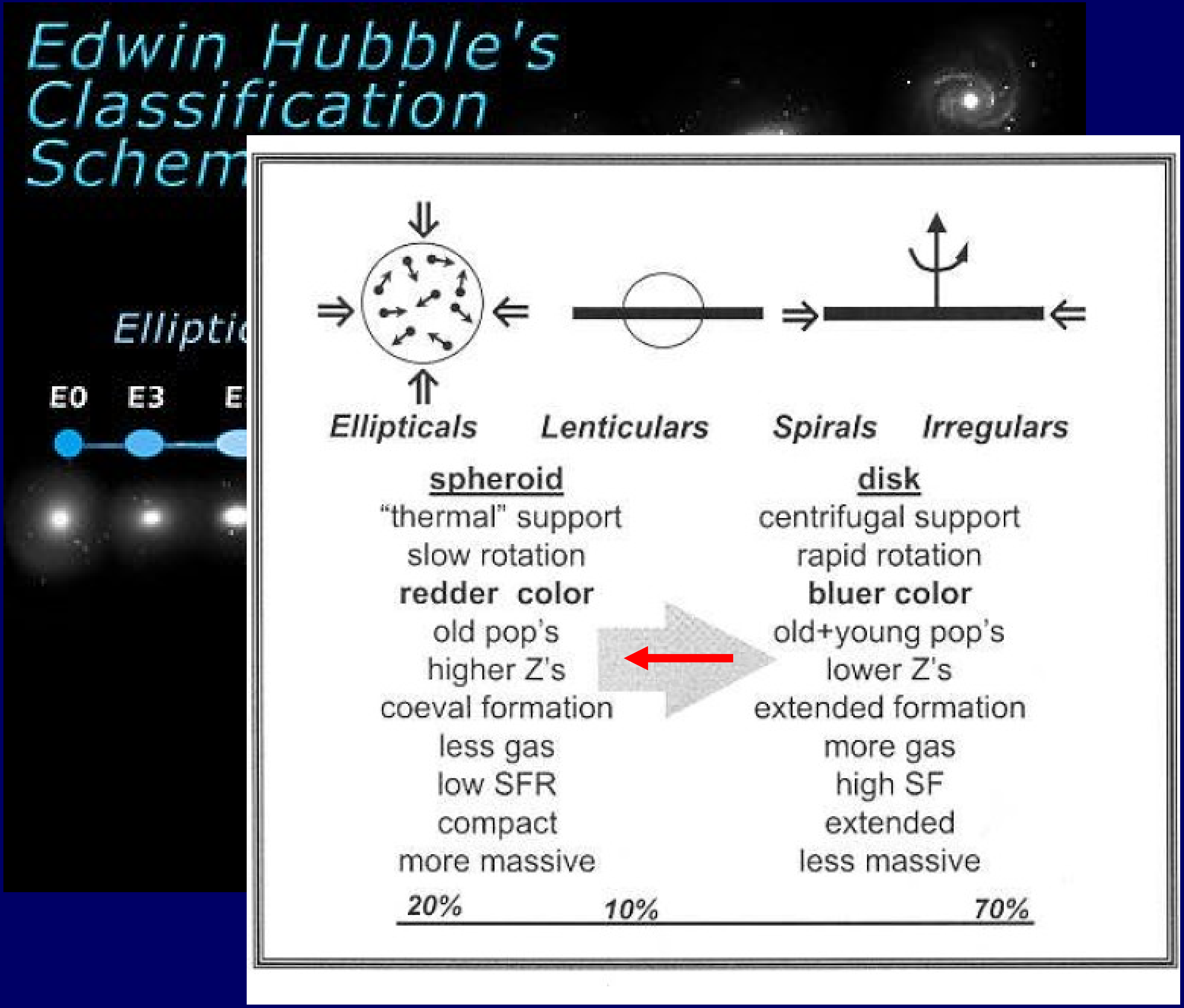
Circular velocity $V_c=(GM/r)^{1/2}$

Virial mass $M = \dfrac{V_c^2 r_{200}}{G} = \dfrac{V_c^3}{10GH(z)}$

$$H(z) = H_0\left[\Omega_{\Lambda,0} + (1-\Omega_{\Lambda,0}-\Omega_0)(1+z)^2 + \Omega_0(1+z)^3\right]^{1/2}$$

CDM halos have central cusps (density diverges towards center)

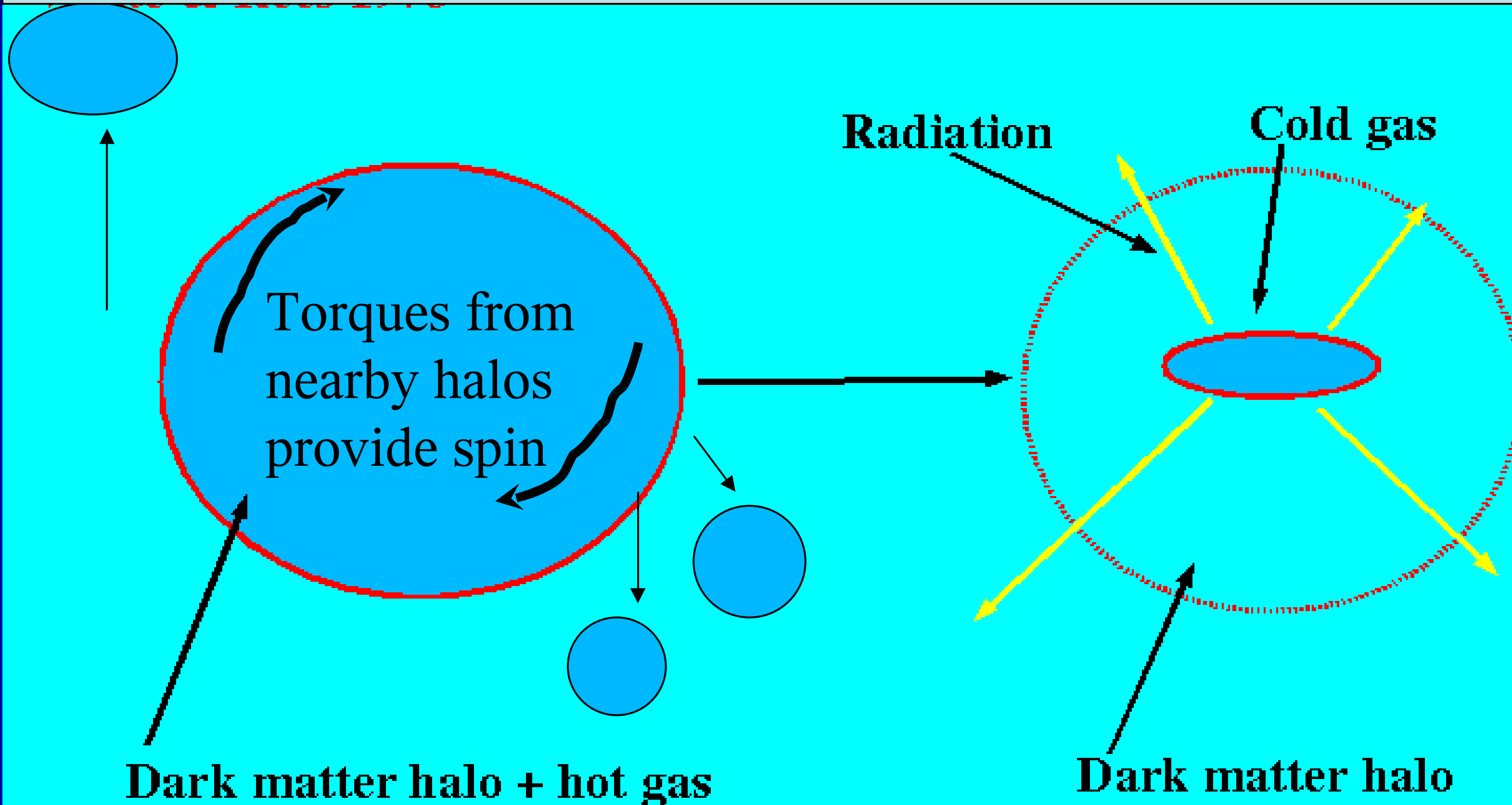
$$\rho_G(r) = \frac{\rho_s}{(r/r_s)^\gamma(1+(r/r_s)^\alpha)^{(\beta-\gamma)/\alpha}}$$ NFW profile has $(\alpha,\beta,\gamma) = (1,3,1)$


Edwin Hubble's Classification Schem
Ellipti
E0
E3
E
Ellipticals
Lenticulars
Spirals
Irregulars
spheroid
"thermal" support
slow rotation
redder color
old pop's
higher Z's
coeval formation
less gas
low SFR
compact
more massive
disk
centrifugal support
rapid rotation
bluer color
old+young pop's
lower Z's
extended formation
more gas
high SF
extended
less massive
20%
10%
70%

Galaxy formation in CDM Universe: baryons in halos

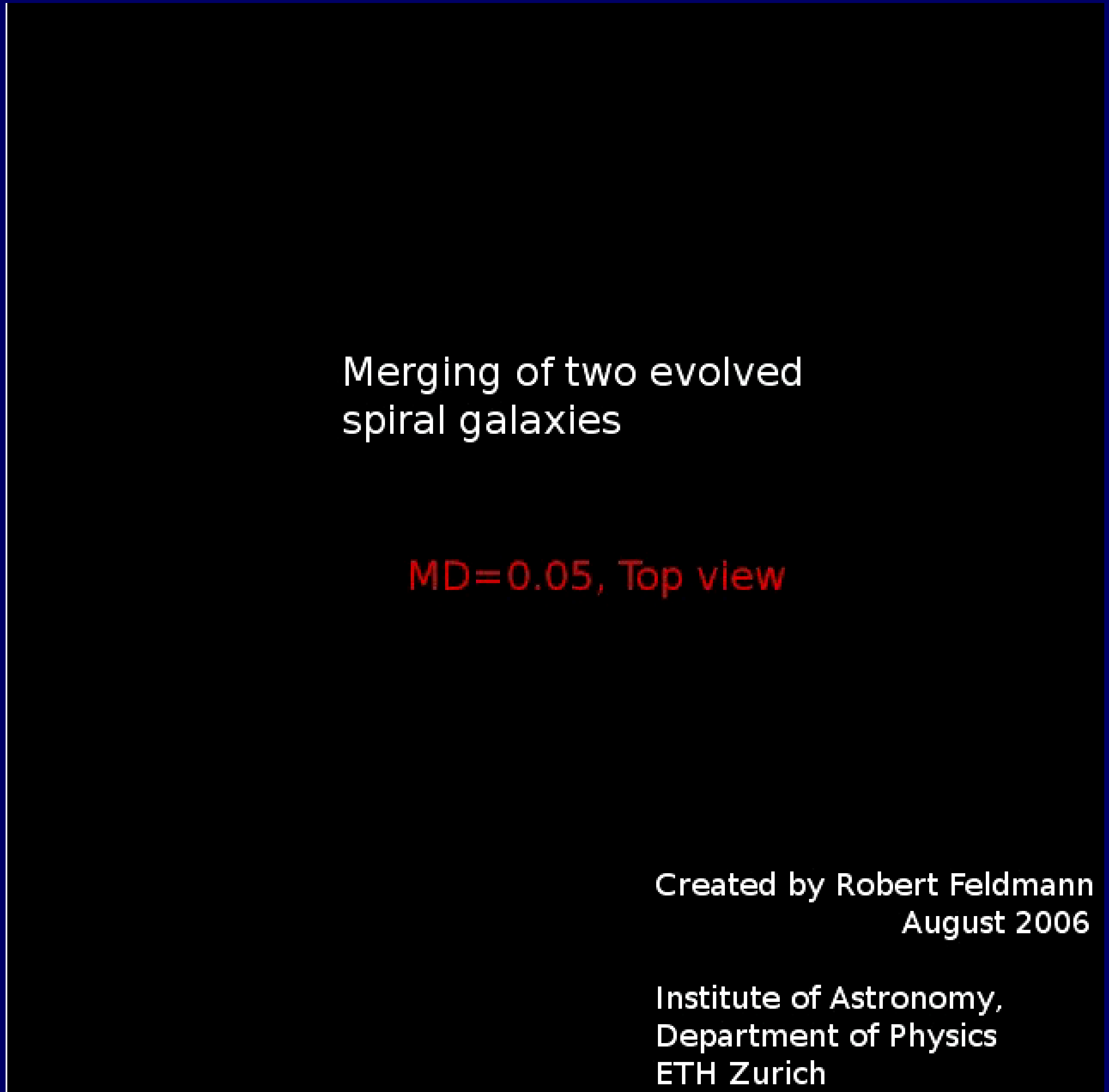
Baryons are captured by the gravity of galaxy-sized dark matter halo

- Cool within halo (Tcool < Thubble) inside-out (density increases towards halo center)
- Form spinning disks - gas settles at radius of centrifugal equilibrium because both gas and dark matter have some angular momentum
- Gas disk forms stars out of the coldest (molecular) phase

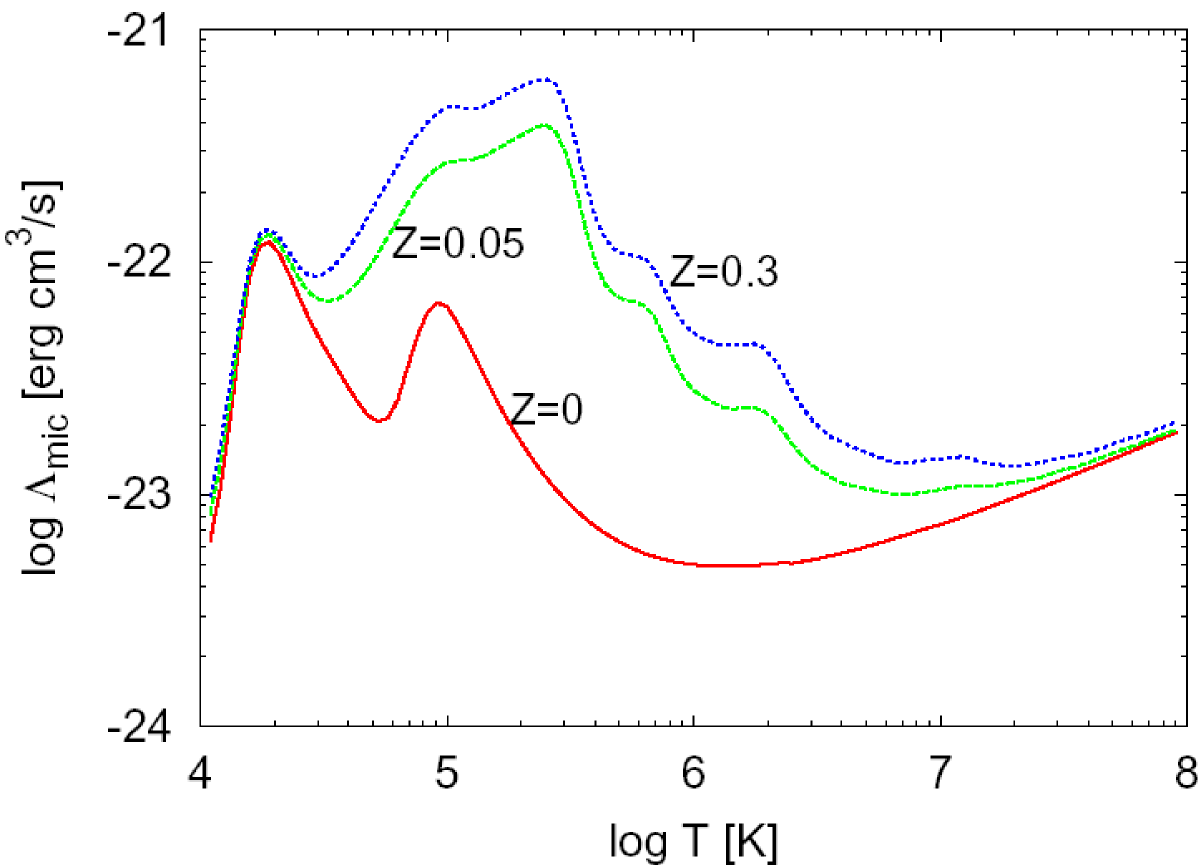


(Fall & Rees 1977;White & Rees, 1978)

Spheroids from mergers of disks – N-Body simulation



Cooling function (assuming ionization equilibrium)



For T < 10^6 K cooling by:
-- Recombination
-- collisional excitation/ radiative decay → peaks in cooling function

Note: cosmic UV bg changes cooling function because changes ion abundance

$$\frac{dE}{dt} = n_e n_H f(T)$$

Cooling rate

$$t_{cool} = \frac{\frac{3}{2}nkT}{n^2\Lambda(T)} = 6.6 \times 10^9 \frac{T_6}{n_{-3}\Lambda_{-24}} \text{ yrs.}$$

$$t_{coll} \simeq \pi\sqrt{\frac{R^3}{GM}} = \left(\frac{3\pi f}{4Gn\mu}\right)^{1/2} = 6.5 \times 10^9 f^{1/2} n_{-3}^{-1/2} \text{ yrs.}$$

Fall & Rees 1977; Silk 1977; White & Rees 1978:

Gas at virial temperature in dark halo first shock heats to virial temperature Tvir and then cools slowly

tcool > tcoll

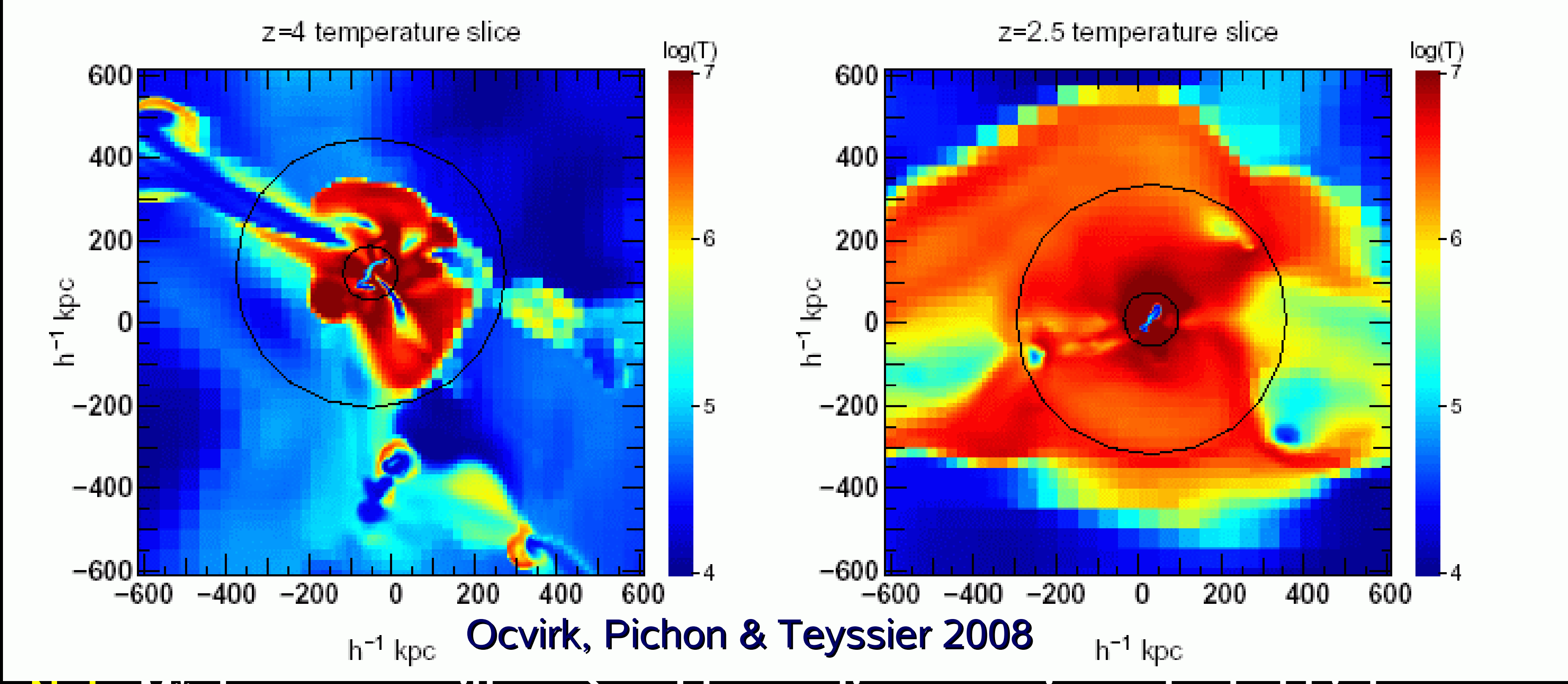
EXAMPLE: 10^{11} Mo gas cloud in 5 x 10^{12} Mo halo, f=Mgal/Mhalo = 0.05 -→

tcool ~ 2 Gyr, tcoll < 1 Gyr

Stability of virial shocks: cold vs. hot accretion

The argument that gas is shock heated when it falls inside dark halos is not true in general (Keres et al. 2005).

- Shocks in infalling gas unstable if $t_{cool} < t_{comp}$



Note:M* decreases with z -→ cold accretion more important at high z

HI filaments of ~ 10^9 Mo detectable out to z ~ 2.5 for a 1000 hours integration with SKA (Van der Hulst et al. 2004)

Formation of disks: basics

The equilibrium properties of a gas disk forming in a dark matter halo (mass, radius, density profile, temperature) depends on:

(6)Gravity

Mostly provided by the dark matter halo, but also by the disk. The disk of a typical spiral galaxy is *self-gravitating*;
EXAMPLE: $M_{dark}/M_{baryon} \sim 1$ at the solar circle in the MW (e.g. Binney & Tremaine 2008)

(2)Gas pressure

Determined by the balance between radiative cooling and heating. heating processes are: (1) shock heating, (2) heating by stellar (UV) irradiation, (3) heating by the uniform cosmic UV background (important at z > 2, see Haardt & Madau 1998, 2001) (4) radiative/turbulent heating by supernovae explosions and supermassive black holes.

(3)Angular momentum

This depends on the initial angular momentum distribution of dark matter and baryons and on how this is exchanged between them, and within them, DURING and AFTER gas collapse

Angular momentum

Spin parameter

A useful definition: the spin parameter

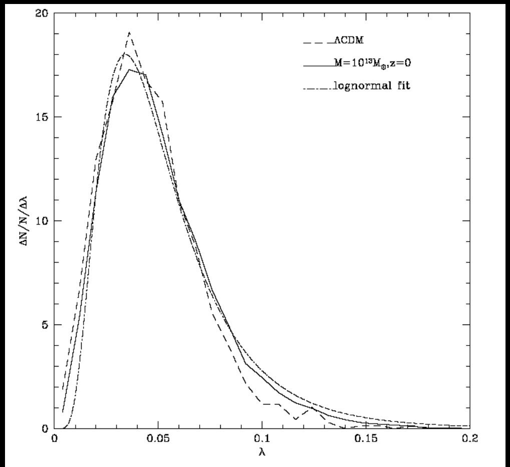
$$\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$$

Meaning of spin parameter (can be verified using isothermal sphere in virial equilibrium, with radius *R*, velocity dispersion σ and *Vrot*= *J/MR*)

$$\lambda \approx 0.4V_{rot}/\sigma$$

Distribution of halo spins from cosmological simulations

Mean λ ~ 0.05



A simple model: Exponential disks in spherical CDM halos (Mo, Mao & White 1998)

(i) Conservation of angular momentum

(ii) $J_{gas}/M_{gas} = J$ ... at t=0 (DM dominant → determines tidal torques)

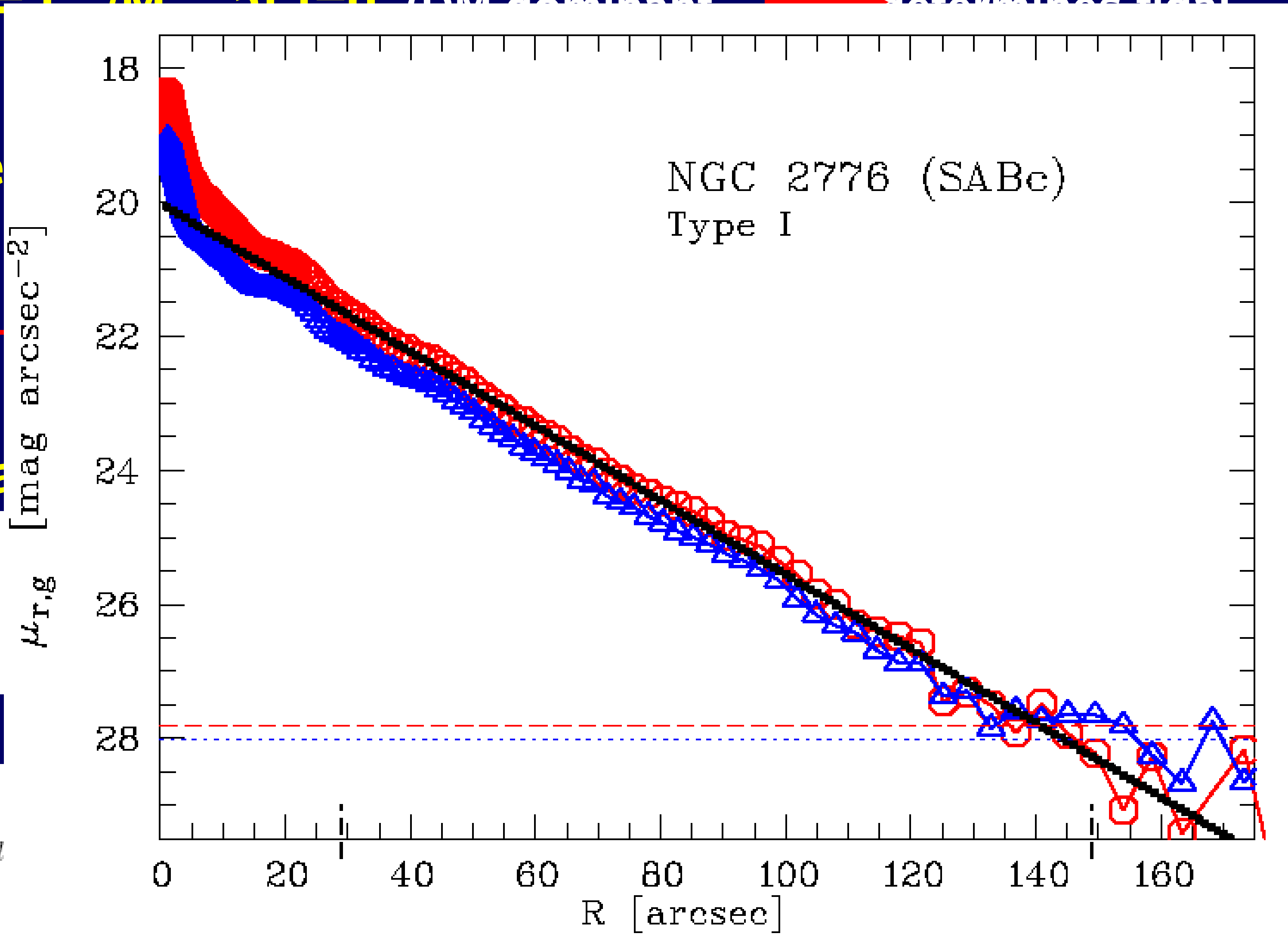
(iii) Expone

For isotherma

spheres

$E =$

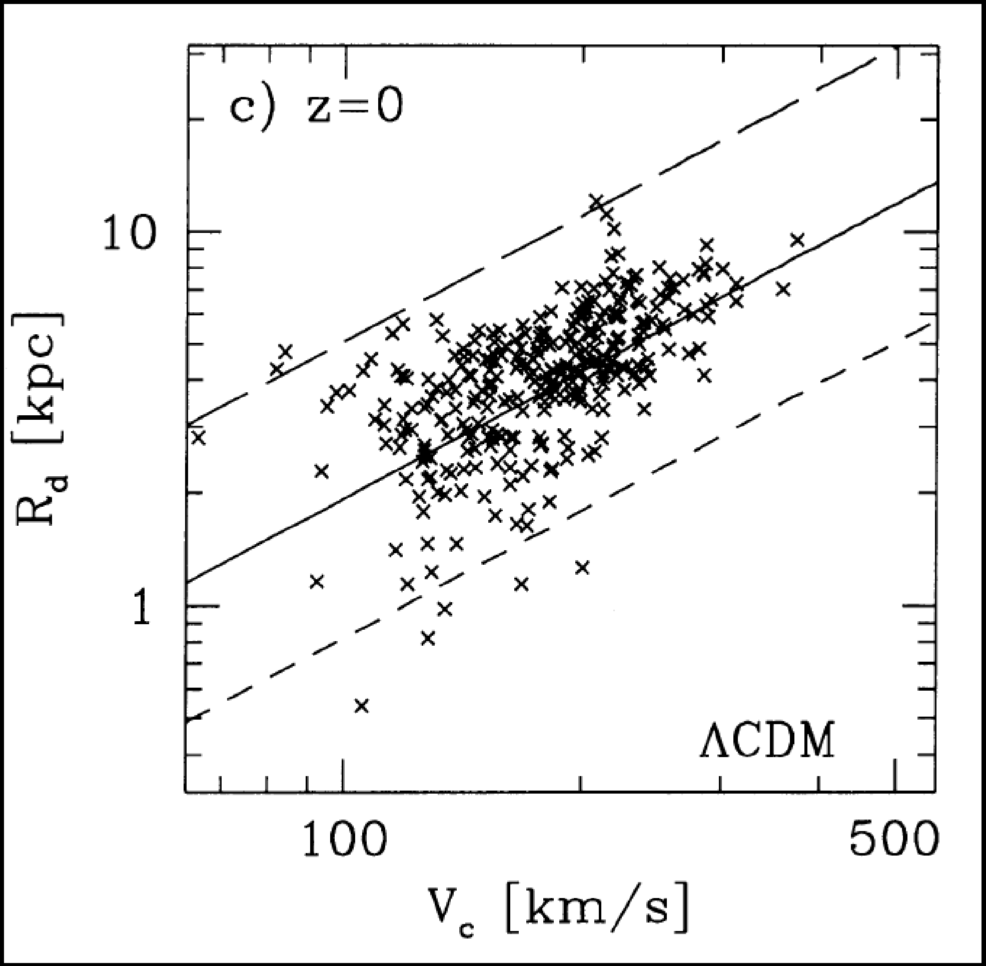
R_d



Semi-analytical models that study the equilibrium disk configuration in an isolated ΛCDM dark halo with assumptions (i), (ii) and (iii) produce disks with realistic sizes

(Mo, Mao & White 1998)

Data points Courteau 1997 (Sb-Sc spirals)

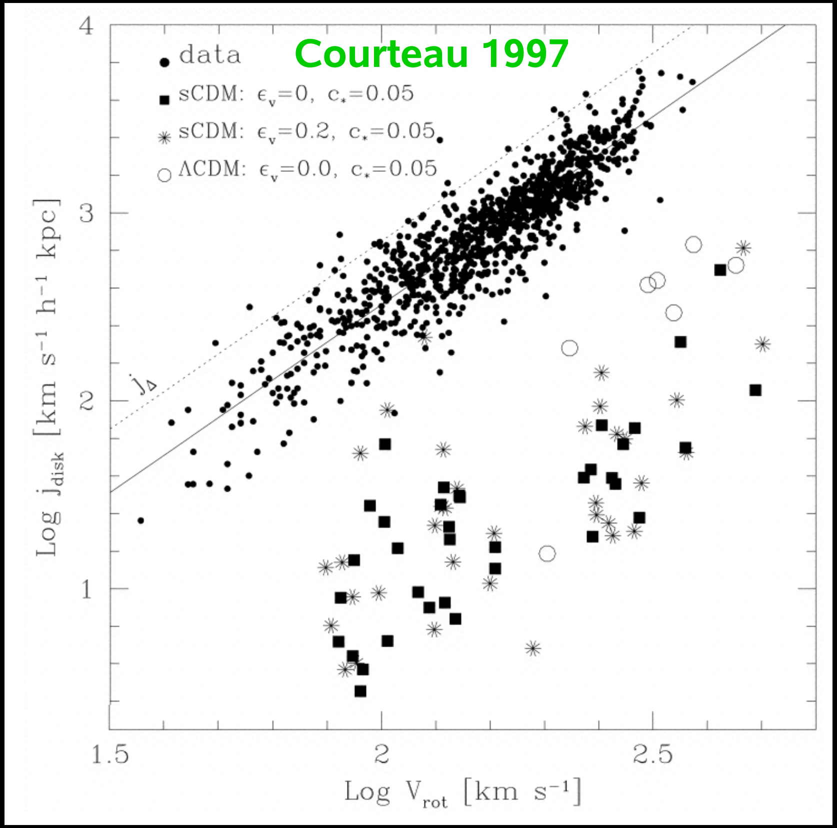


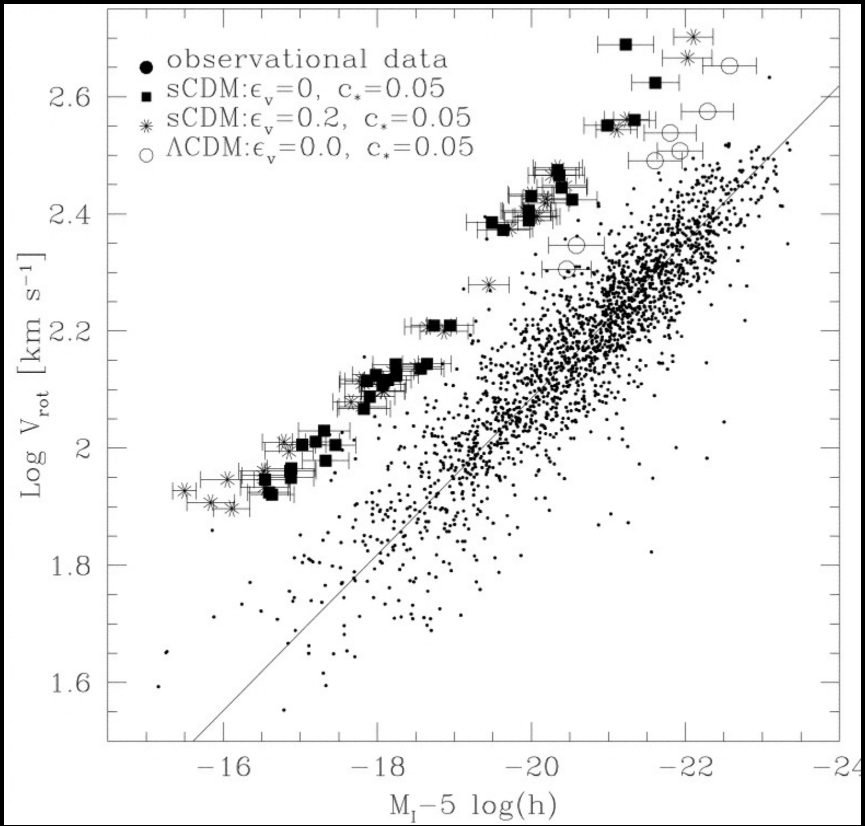
Inspiring result: CDM halos have the right J to yield correct disk formation (if conservation of J and the other assumptions hold true…)

Angular Momentum Problem:scaling laws

Disks are too small at a given rotation speed (Vrot=Vcirc= measure of mass)

Disks rotate too fast at a given luminosity -> disks too compact so Vrot ~ $(GM/R_{disk})^{1/2}$ too high

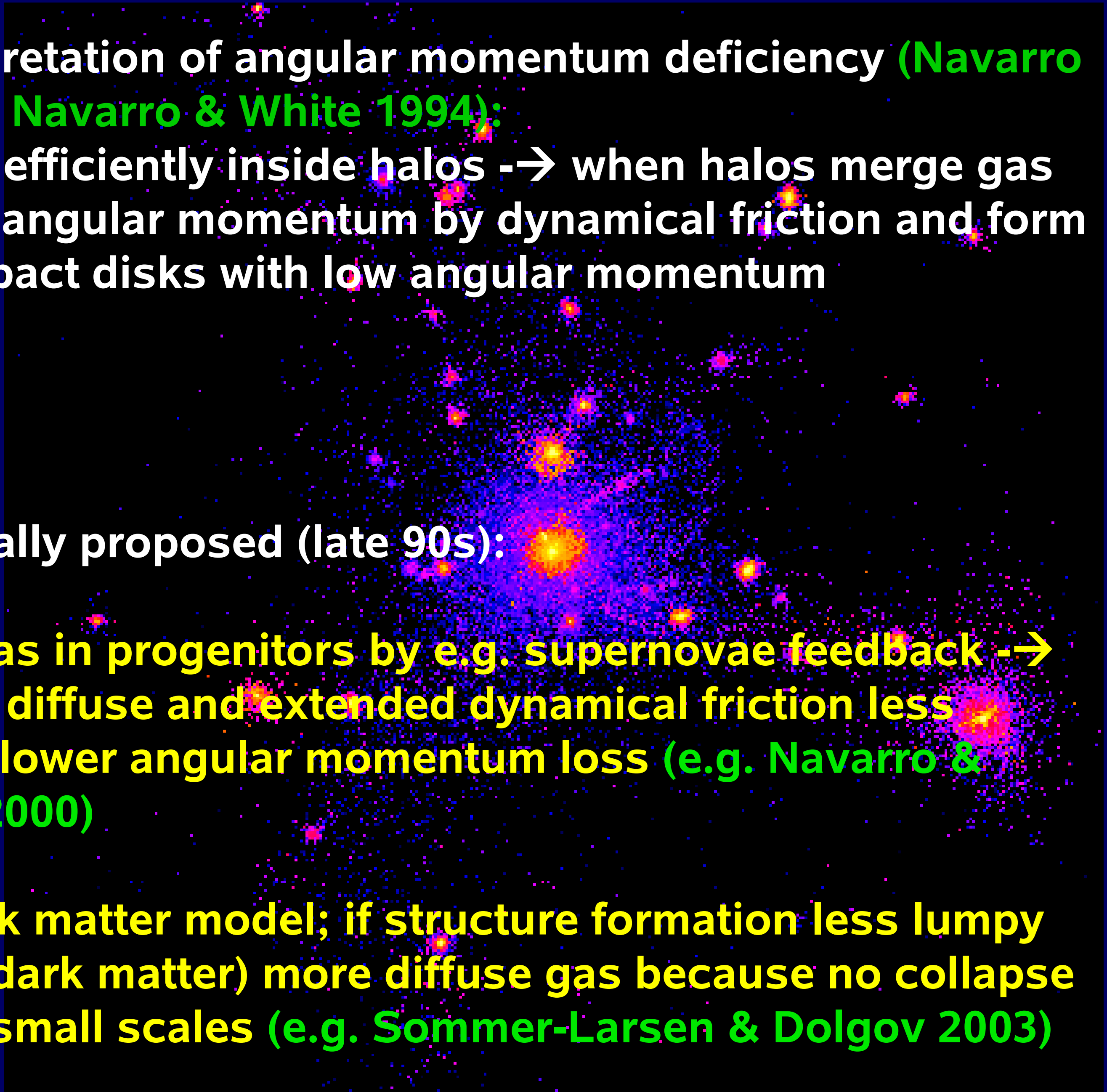




Navarro & Steinmetz 2000

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

Is disk formation CDM-compatible?



Original interpretation of angular momentum deficiency (Navarro Benz 1991, Navarro & White 1994):

Gas cools too efficiently inside halos -→ when halos merge gas lumps lose angular momentum by dynamical friction and form small, compact disks with low angular momentum

Solutions initially proposed (late 90s):

(11)Heat the gas in progenitors by e.g. supernovae feedback -→ if gas more diffuse and extended dynamical friction less efficient-→ lower angular momentum loss (e.g. Navarro & Steinmetz 2000)

(2)Change dark matter model; if structure formation less lumpy (e.g. warm dark matter) more diffuse gas because no collapse in halos at small scales (e.g. Sommer-Larsen & Dolgov 2003)

GALAXY FORMATION – A MULTI-FACETED PROBLEM

TO SOLVE IT WE NEED:

- **RIGHT COSMOLOGY/STRUCTURE FORMATION** - provides the initial conditions (e.g. J, halo masses/densities) and the global dynamics (hierachical merging/accretion). Let us assume ΛCDM model is correct.

- **"COMPLETE" INPUT PHYSICS** radiative cooling, star formation,heating mechanisms in interstellar medium (supernovae explosions, radiative backgrounds, e.g. cosmic UV bg) ---→ should yield right thermodynamics of baryons.

↕

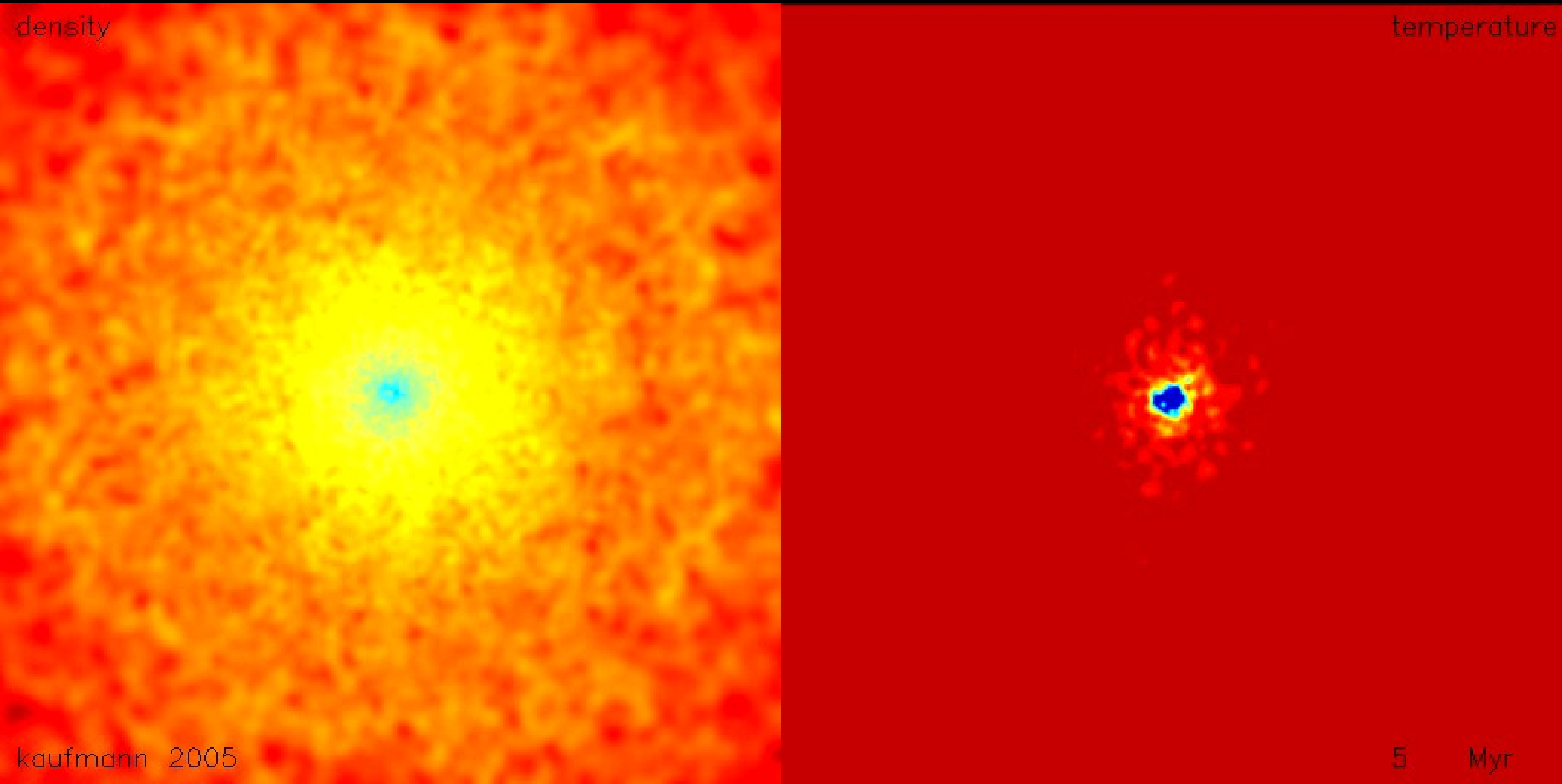
- **RELIABLE NUMERICAL MODELS**

Numerical simulations (needed due to complexity) rely on discrete representation + solution of continuum CDM and baryonic fluid by particles/finite grid cells → solve exactly Collisionless Boltzmann Equation (CDM) and Euler equation (baryons) coupled with gravity only in the limit of infinite number of particles/grid cells…

3D Isolated galaxy collapse simulation

Gas collapses in isolated CDM halo with initial $J(r) \sim r^{-1.1}$
(J(r) consistent with cosmological simulations, Bullock et al. 2000)
No large scale cosmological density field ---→ can use plenty of particles in a single system

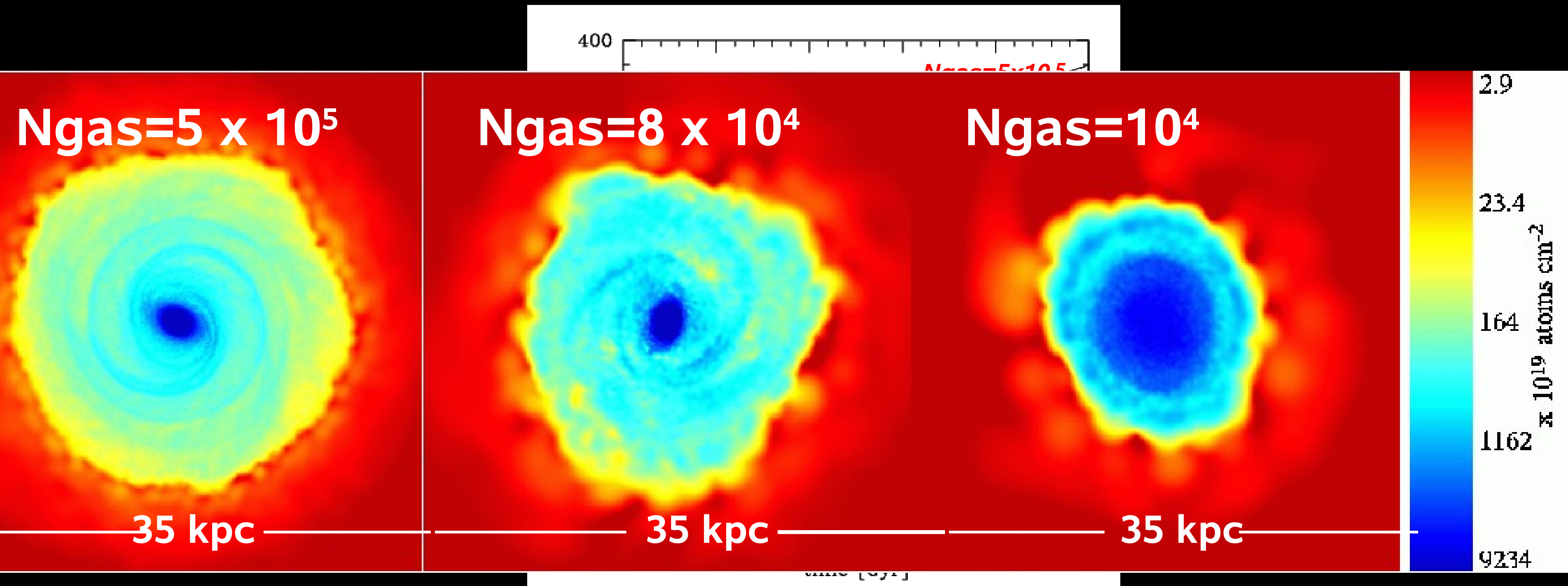
Kaufmann, Mayer et al. (2006, 2007).



Numerical issues: angular momentum convergence

Kaufmann, Mayer et al. 2007

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



Conservation of J improves with increasing Ngas.

Convergence not reached even with ~ 10^6 gas particles but loss of angular momentum down to < 20% at max. resolution

Gas particles in a sphere of initial radius ~ cooling radius = 80 kpc are followed. These particles end up in the disk , i.e. they trace the angular momentum evolution of disk material

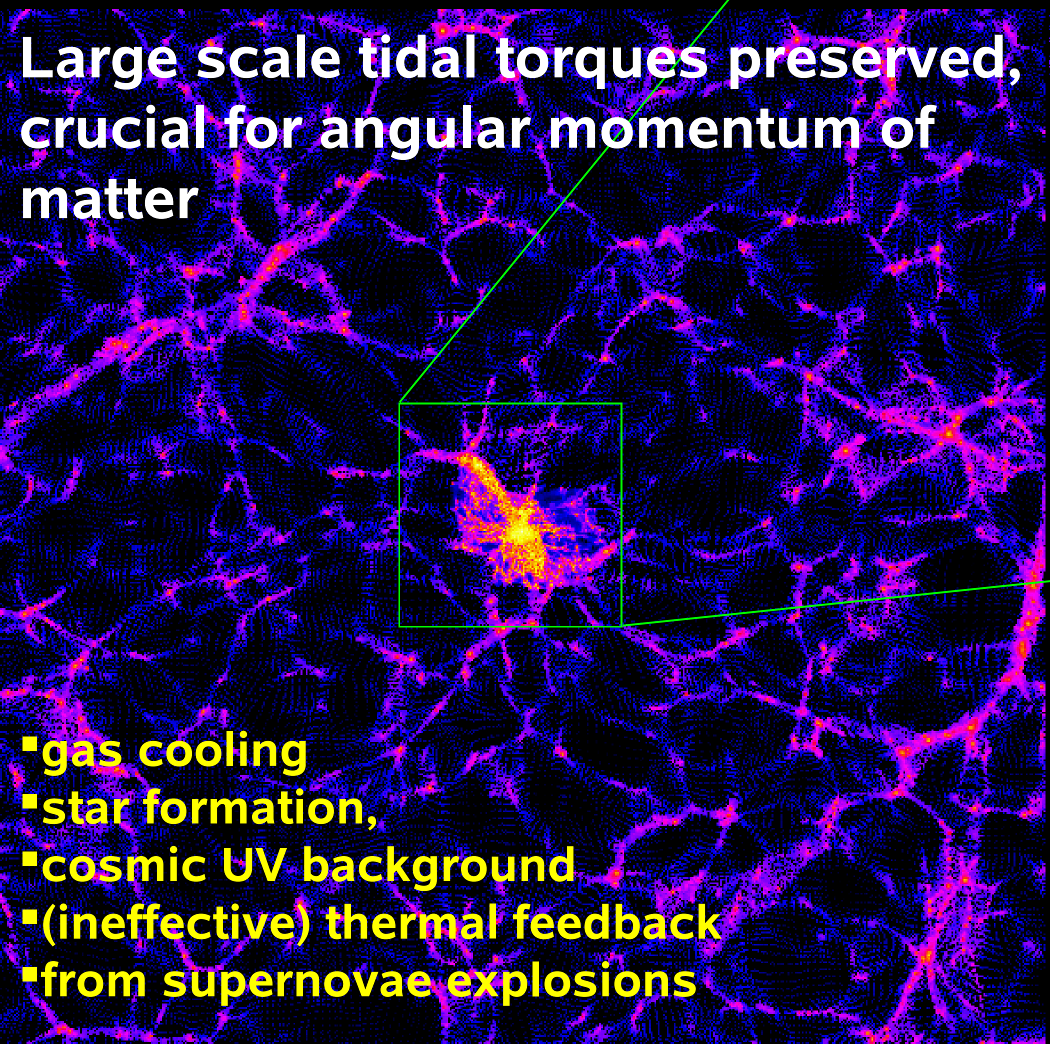
Artificial loss of J in SPH simulations due to:

(1)Artificial viscosity torques; (2) spurious hydro torques between cold disk and surrounding hot phase; (3) spurious gravitational torques between cold gas and hot halo

High resolution galaxy formation

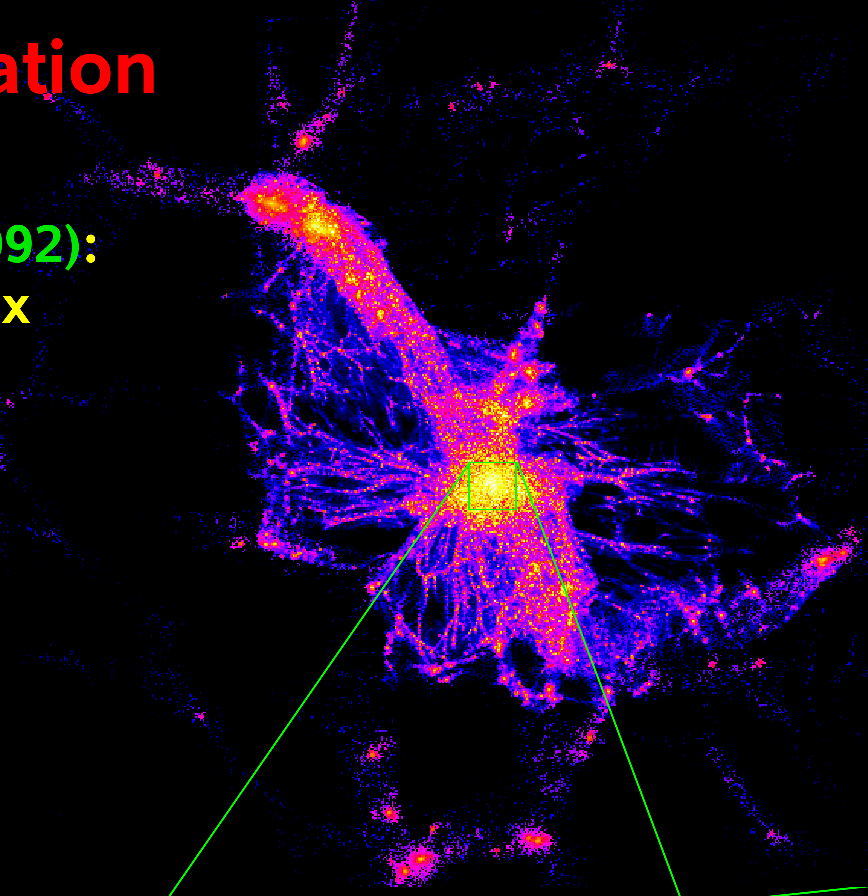
(Governato, Mayer et al. 2004)

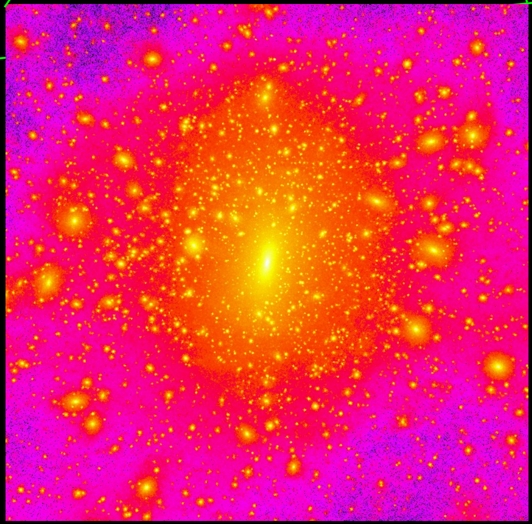
Multi-mass refinement technique (Katz 1992):
< 1kpc spatial resolution in a 100Mpc box
(DM + GAS)



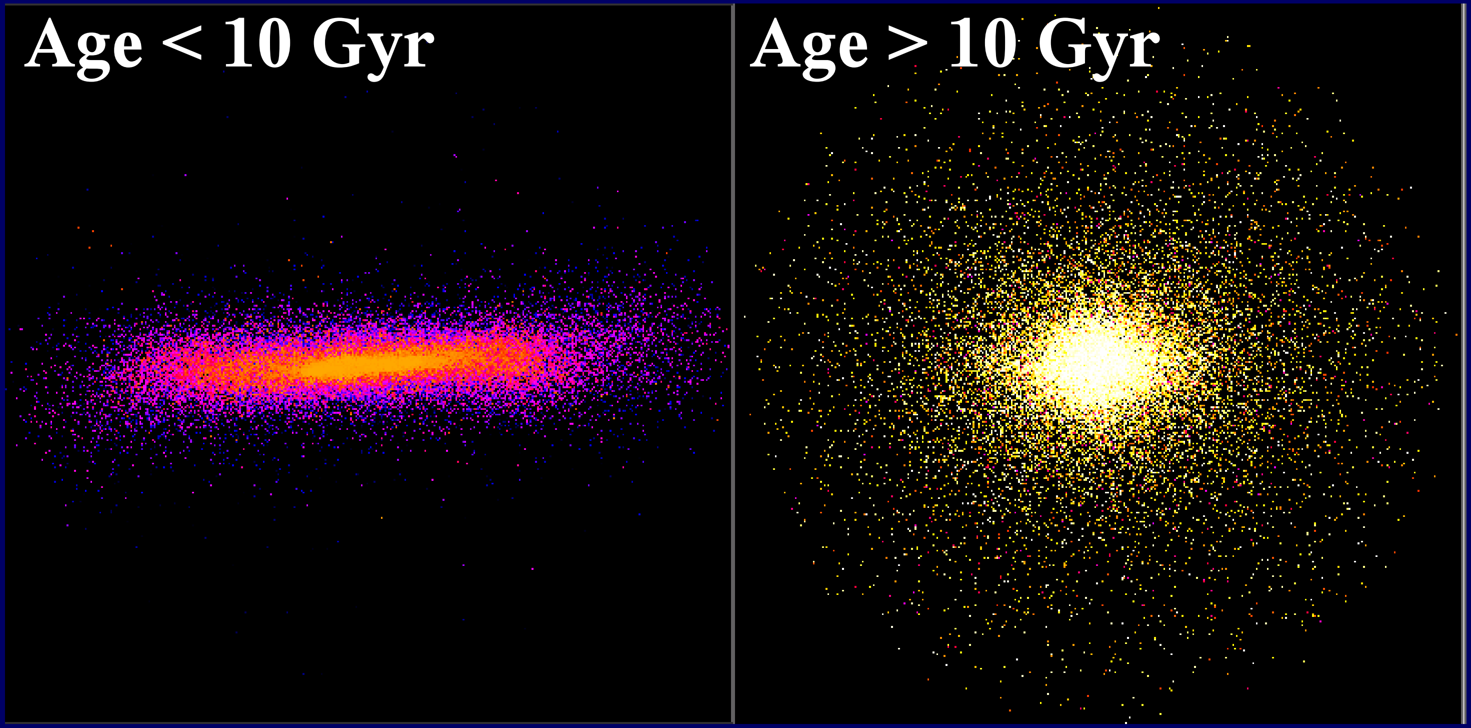
Large scale tidal torques preserved, crucial for angular momentum of matter

- gas cooling
- star formation,
- cosmic UV background
- (ineffective) thermal feedback
- from supernovae explosions





A ΛCDM MW-sized galaxy at z=0
Ngas,dm ~ 10^5



Frames of 30 kpc on a side

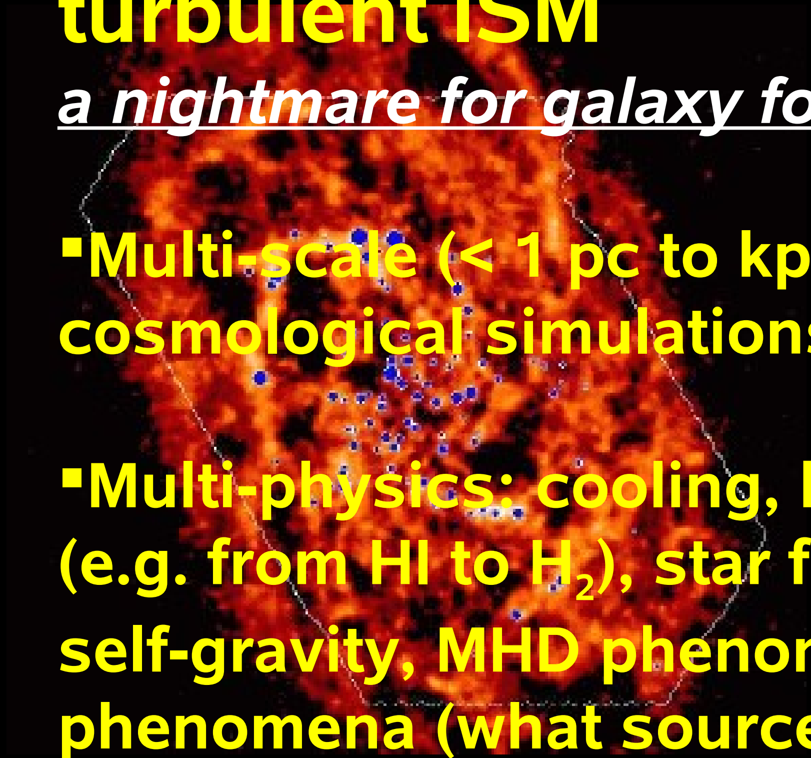
Disk (+ bar) **Bulge + Stellar Halo**

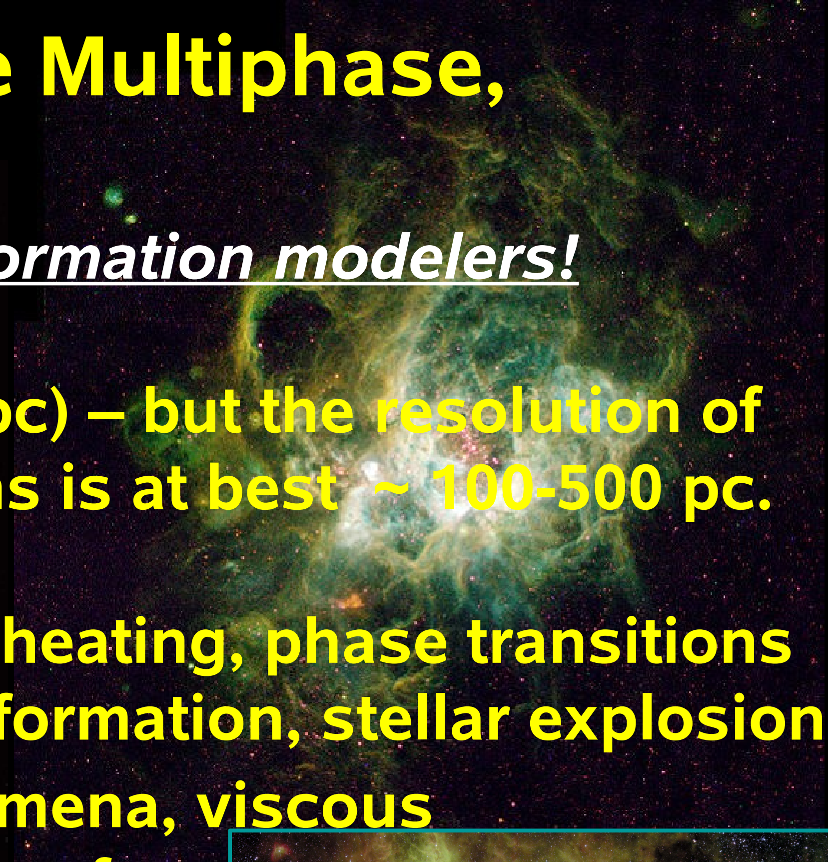
Stellar ages are shown (brighter colors for younger ages) boxes are 40 kpc

- Galaxy has Mbulge/Mdisk ~ 0.5, while Mbulge/Mdisk ~ 0.2 in MW.
- Mdisk ~ Mdisk (MW) but a factor of 2 too small compared to MW

Input physics: The Multiphase, turbulent ISM

<u>a nightmare for galaxy formation modelers!</u>

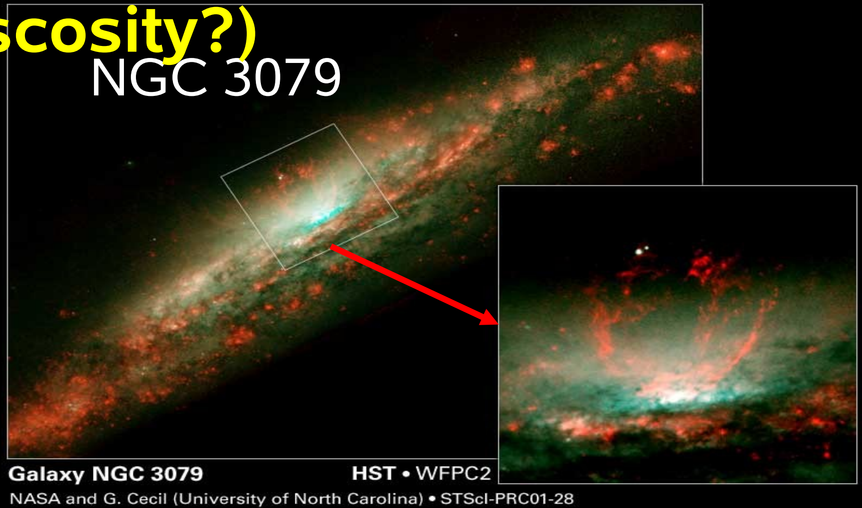


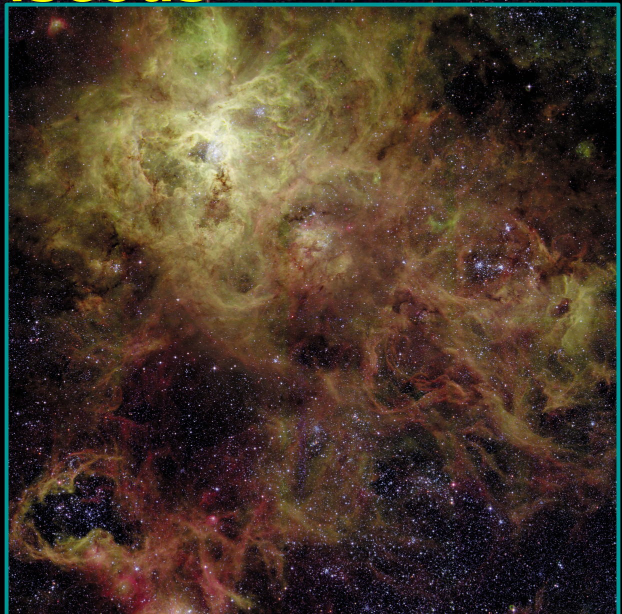


- Multi-scale (< 1 pc to kpc) – but the resolution of cosmological simulations is at best ~ 100-500 pc.

- Multi-physics: cooling, heating, phase transitions (e.g. from HI to H_2), star formation, stellar explosions, self-gravity, MHD phenomena, viscous phenomena (what source of viscosity?)

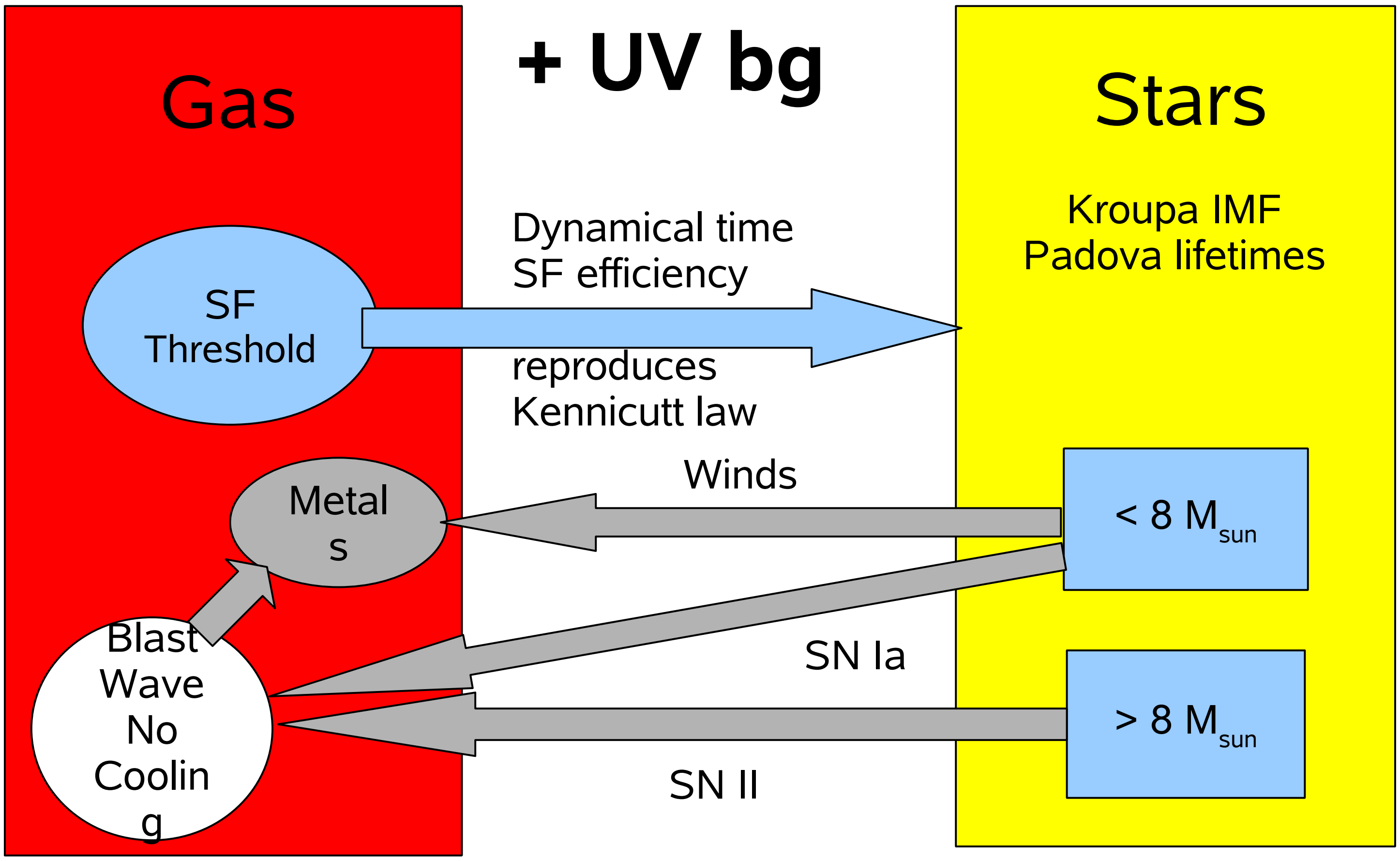
NGC 3079





A (sub-grid) attempt to model ISM physics

Stinson et al 2006

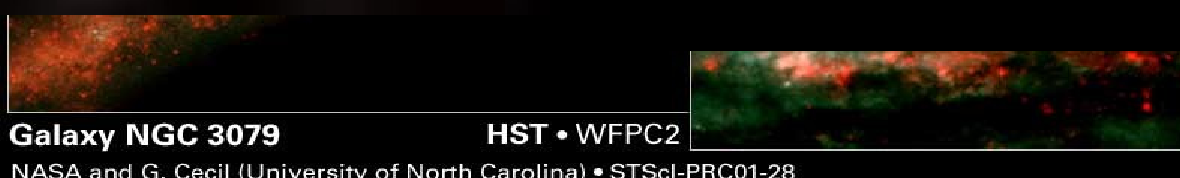


2 free parameters: C* (SF efficiency), eSN (supernova heating efficiency)

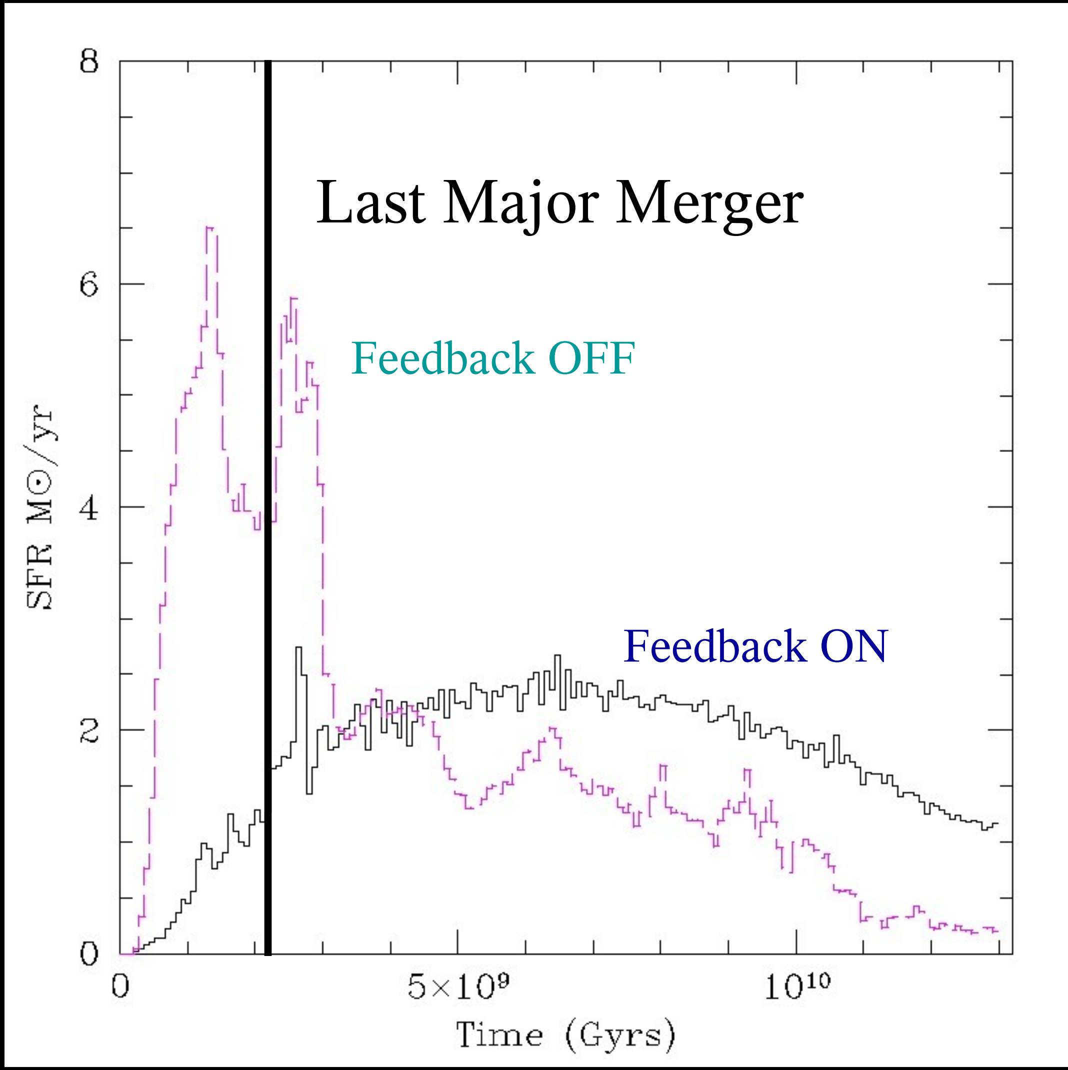
Supernova blast-wave model based on **McKee & Ostriker (1977)**

Key feature of sub-grid model **: cooling stopped in region surrounding supernovae explosions for t ~ 10^7 years**

- *Mimics adiabatic expansion phase of supernova blast wave (Sedov-Taylor phase). Volume of region affected by blast waves self-consistently calculated based on McKee & Ostriker (1977)*
- *Cooling shut-off imescale also of the same order of estimated decay time of interstellar turbulence (Klessen & MacLow 2002)*



Effect of SN feedback on SFH of a 10^{11} Solar Masses Galaxy

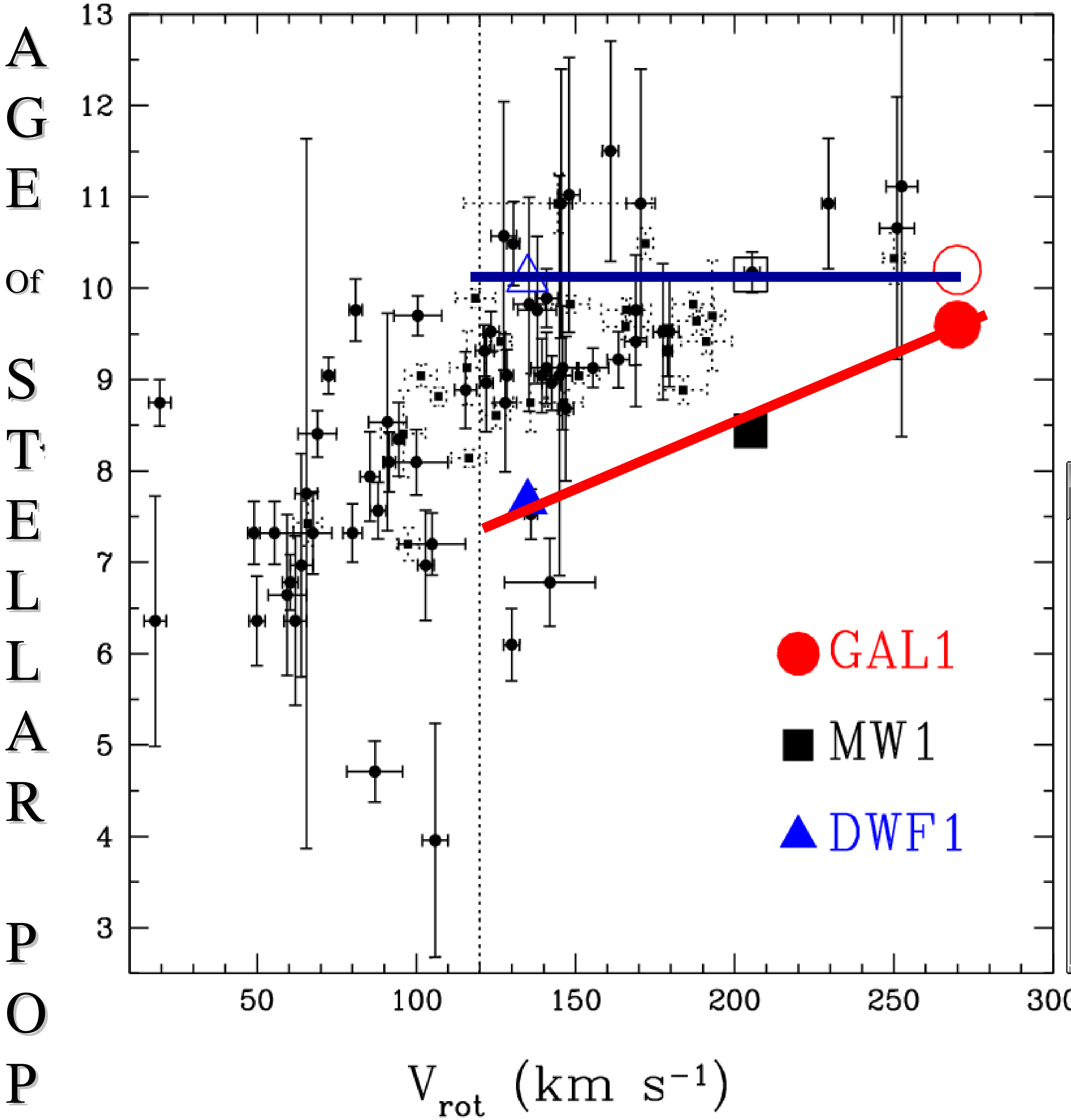


SFH includes all progenitors at any given time

Without "blastwave" feedback (only thermal feedback) star formation history follows merging history.

If "blastwave" feedback is on, star Formation peaks at $z < 1$ AFTER Last Major Merger.

Early mergers inefficient and gas rich
SF in bulges suppressed.



Mac Arthur Courteau and Bell 2004

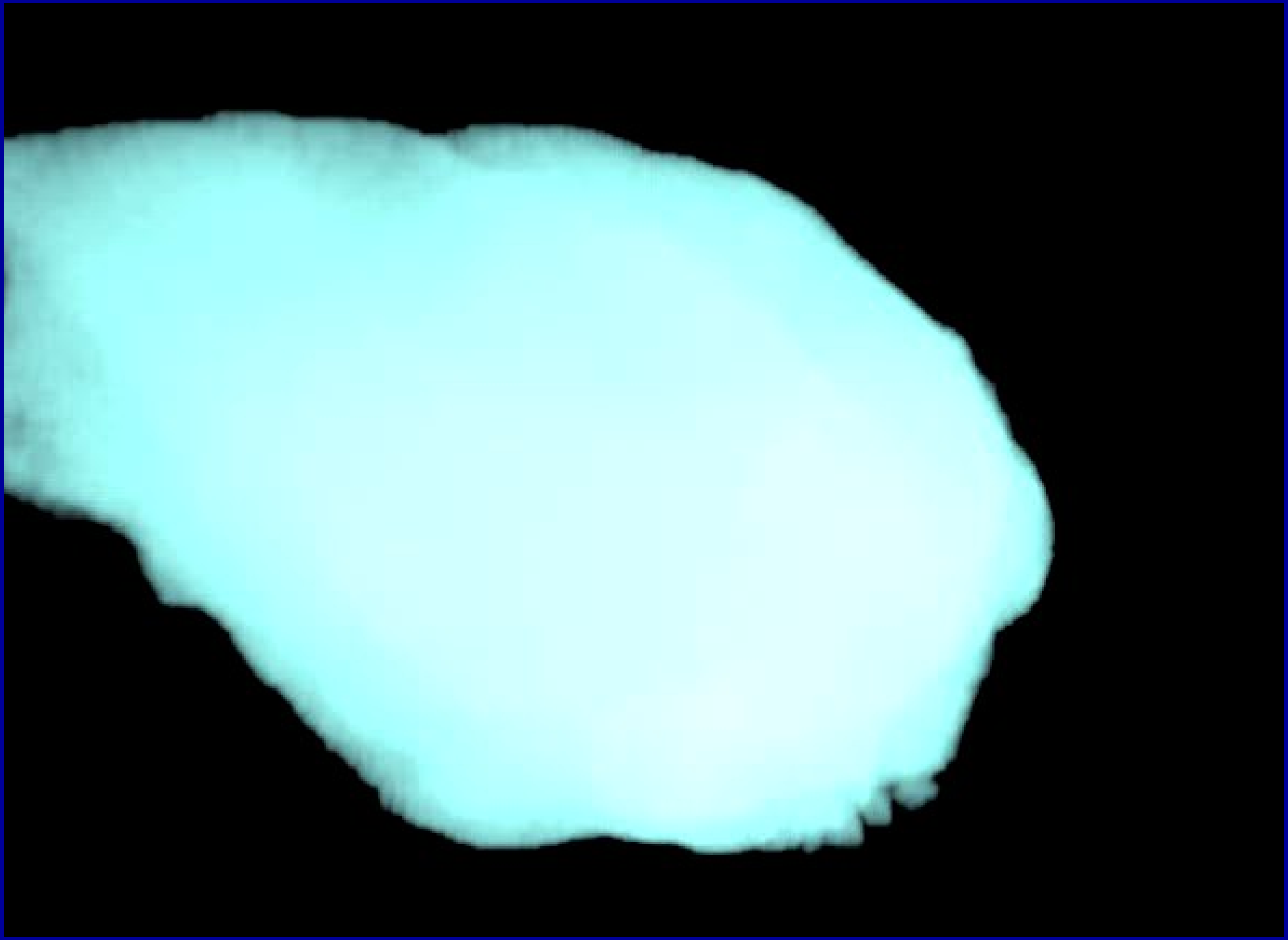
Runs with SN Feedback reproduce the observed Vrot vs Age trend.

Star Formation delayed/suppressed in small progenitors.

State-of-the art cosmological hydro simulation of MW-sized galaxy formation.

Last major merger at z ~ 2, then fairly quiescent evolution with only a few accretion episodes

(Ngas, Ndm ~ 2 x 10^6 within R < Rvir + blast-wave feedback model)

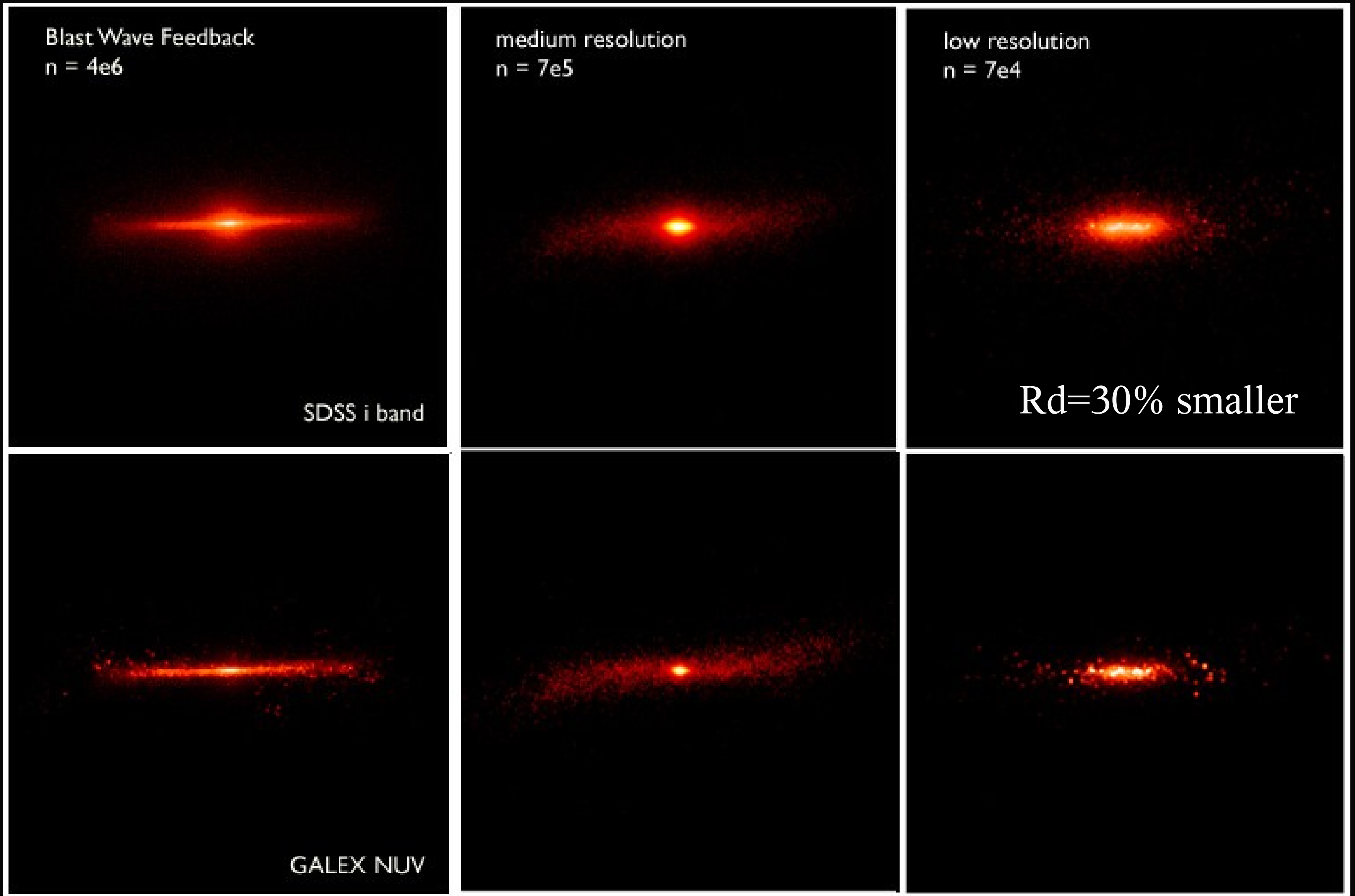


Frame size = 100 kpc comoving

(Governato, Willman, Mayer et al. 2006, 2007)

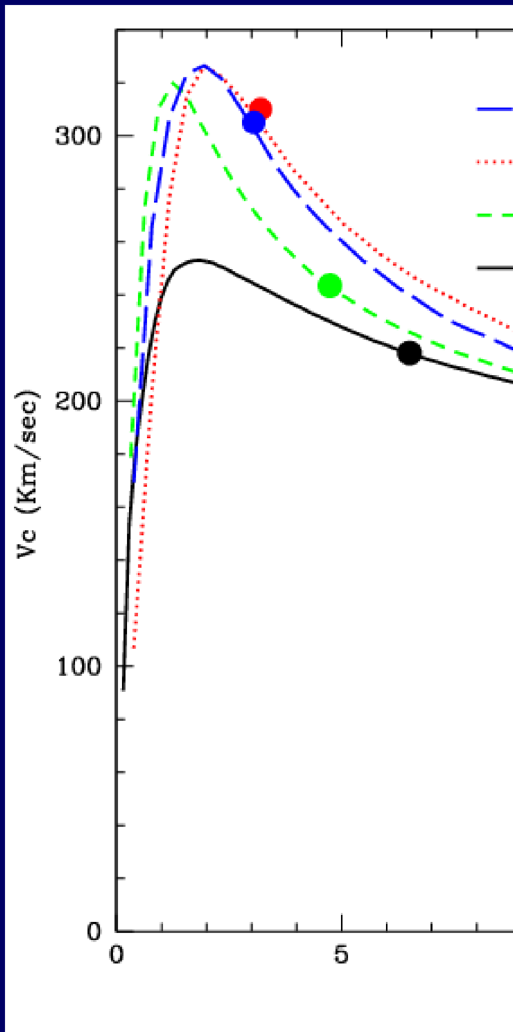
Effect of Increasing Resolution on the size of disks

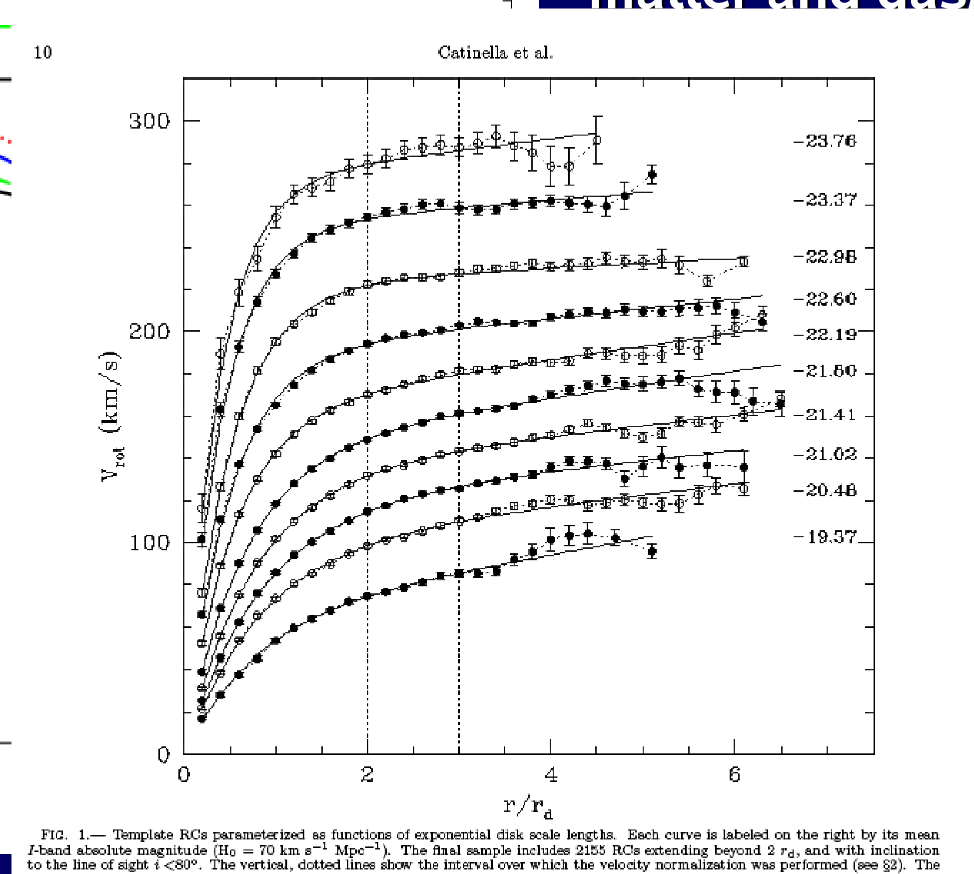
N=DM+Gas+stars



Rotation curve vs. resolution

Rotation curve measures central mass concentration





Low-res = 3.5×10^4 **dark matter and gas/star**

.5 x 10^5 dark
/star

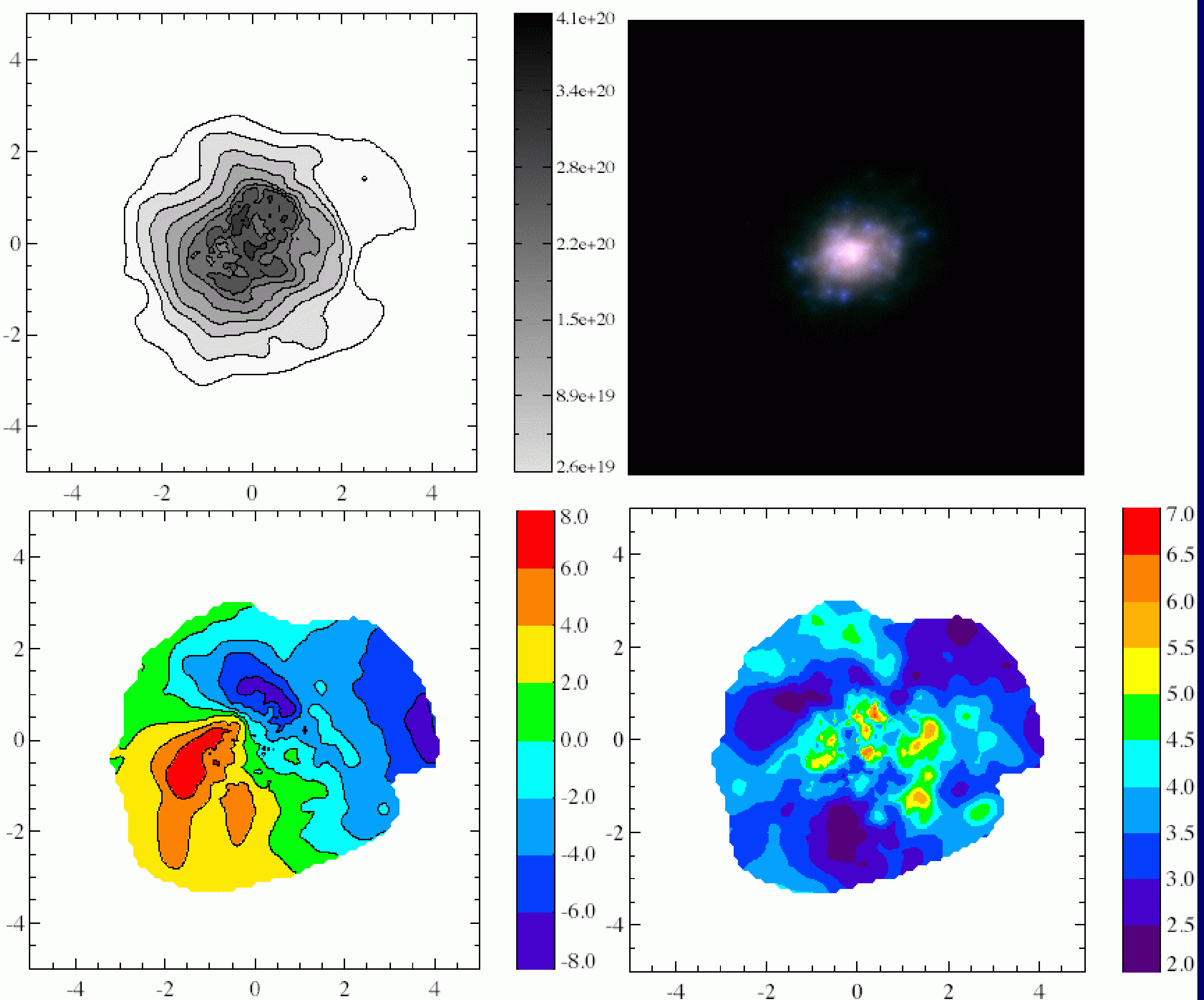
dark matter
rticles

At high resolution rotation curve begins to resemble that of an early-type spiral galaxy (e.g. M31)

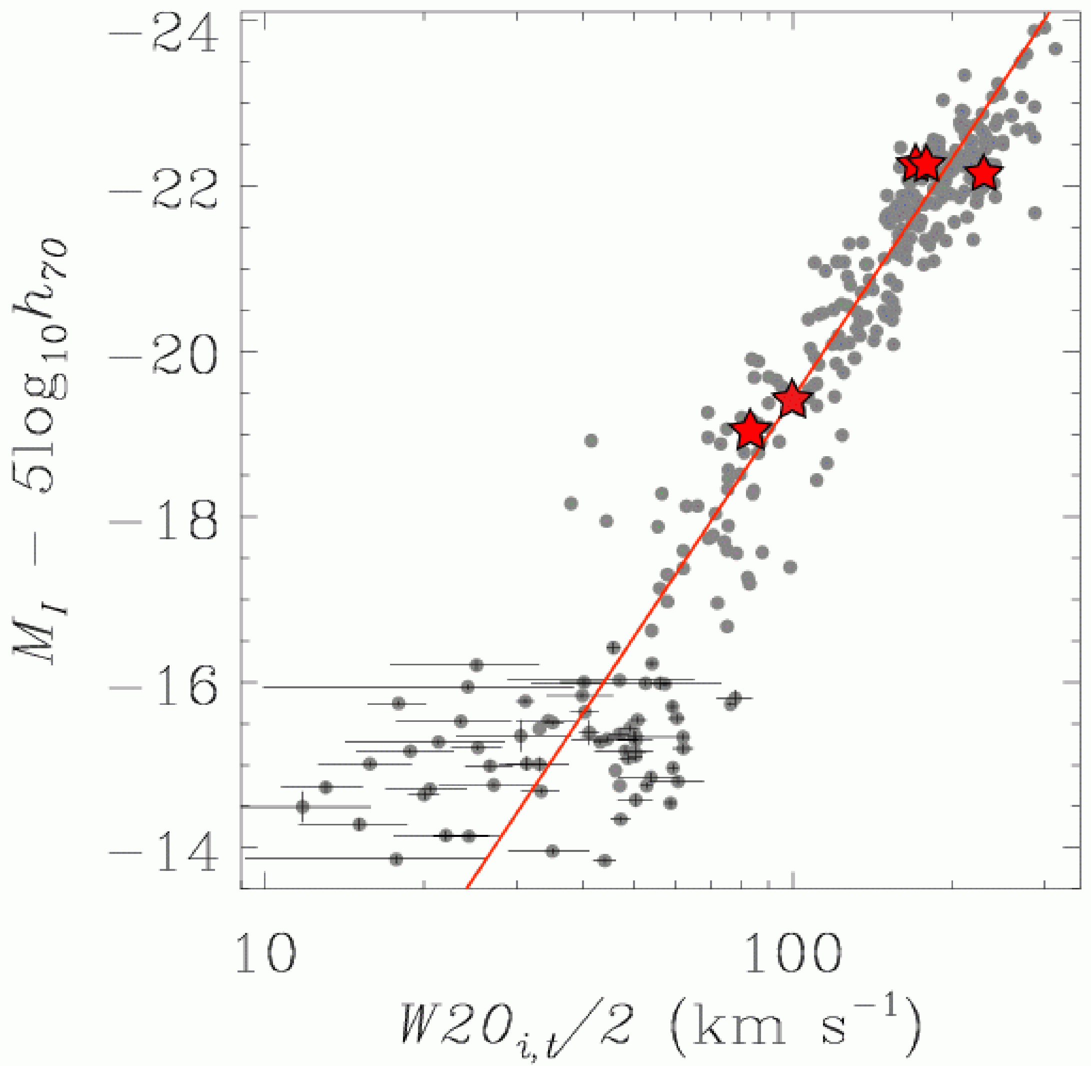
Mock HI observations from simulations

Slip et al. in prep

GASOLINE now includes calculation of HI fraction in presence of UV background, including self-shielding effects



HI and optical maps generated from a **simulated** isolated test dwarf galaxy. The x and y scales are in kpc. ***Upper left:*** The HI column density in atoms cm^{-2}. ***Upper right:*** A three-color u, g, r image. ***Lower left:*** The HI velocity field in km s^{-1}. ***Lower right:*** The HI velocity dispersion in km s^{-1}.

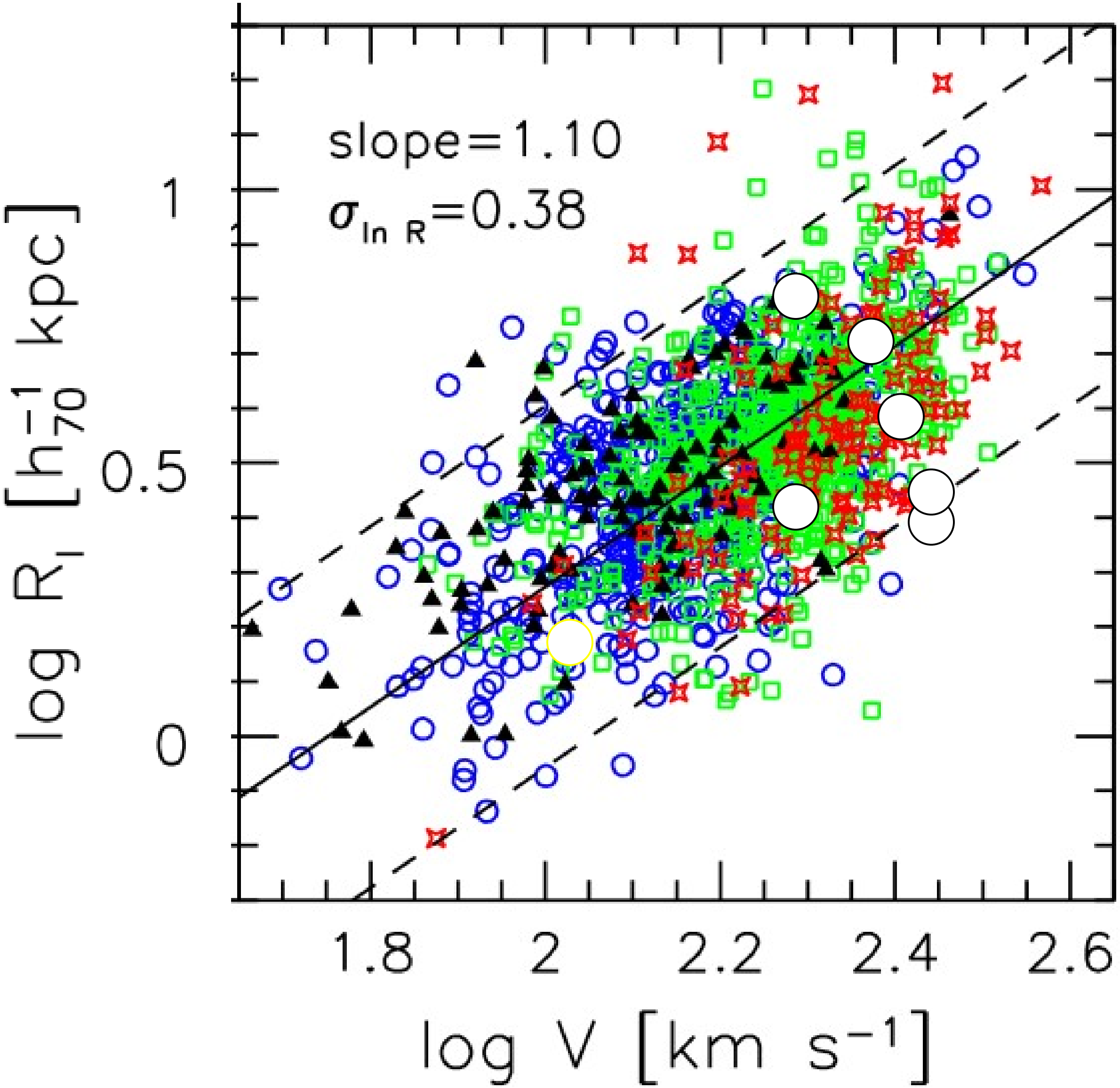


The Tully-Fisher Relation

The **simulated halos** (stars) on a plot of the Tully-Fisher relation from Geha et al. (2006), using measured HI widths and I-band magnitudes. The grey background points are from a variety of sources as cited in Geha et al. (2006).

Simulations have now enough resolution to study evolution of TF from z = 2 to z = 0 (progenitors of final galaxy well resolved)--→ synergy with future deep HI emission surveys by e.g. SKA

The Velocity- Size Relation



Courteau 07

Sa

High Res

V: W20
Mag: Sunrise

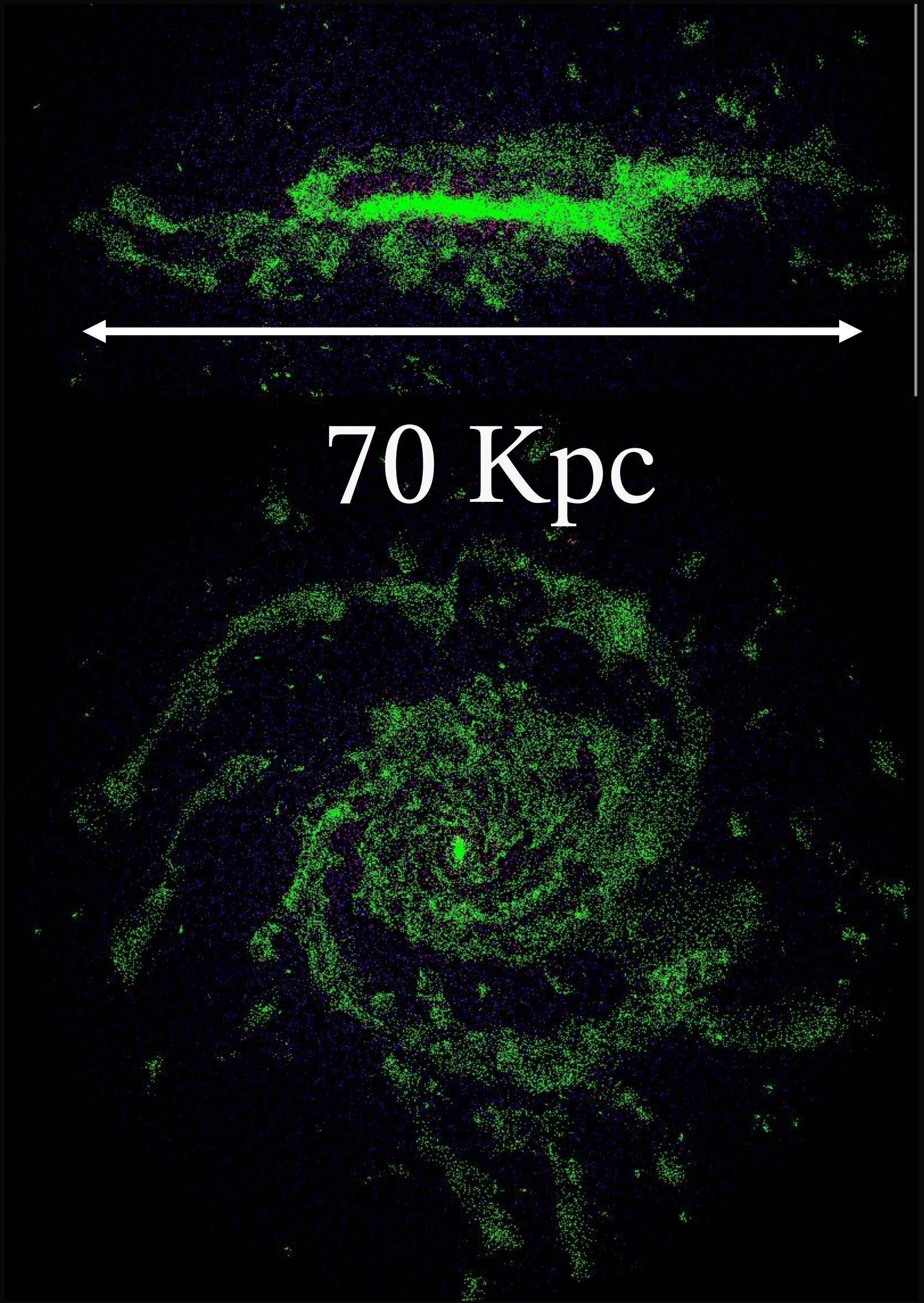
Another MW-sized galaxy, but with a different merging history. Last major merger at z ~ 1 plus several minor mergers at z < 0

(Ngas, Ndm > 10^6 within R < Rvir + blast-wave feedback model)

(Mayer, Governato and Kaufmann 2008; Governato et al., in preparation)

Frame size = 200 kpc comoving

HI map

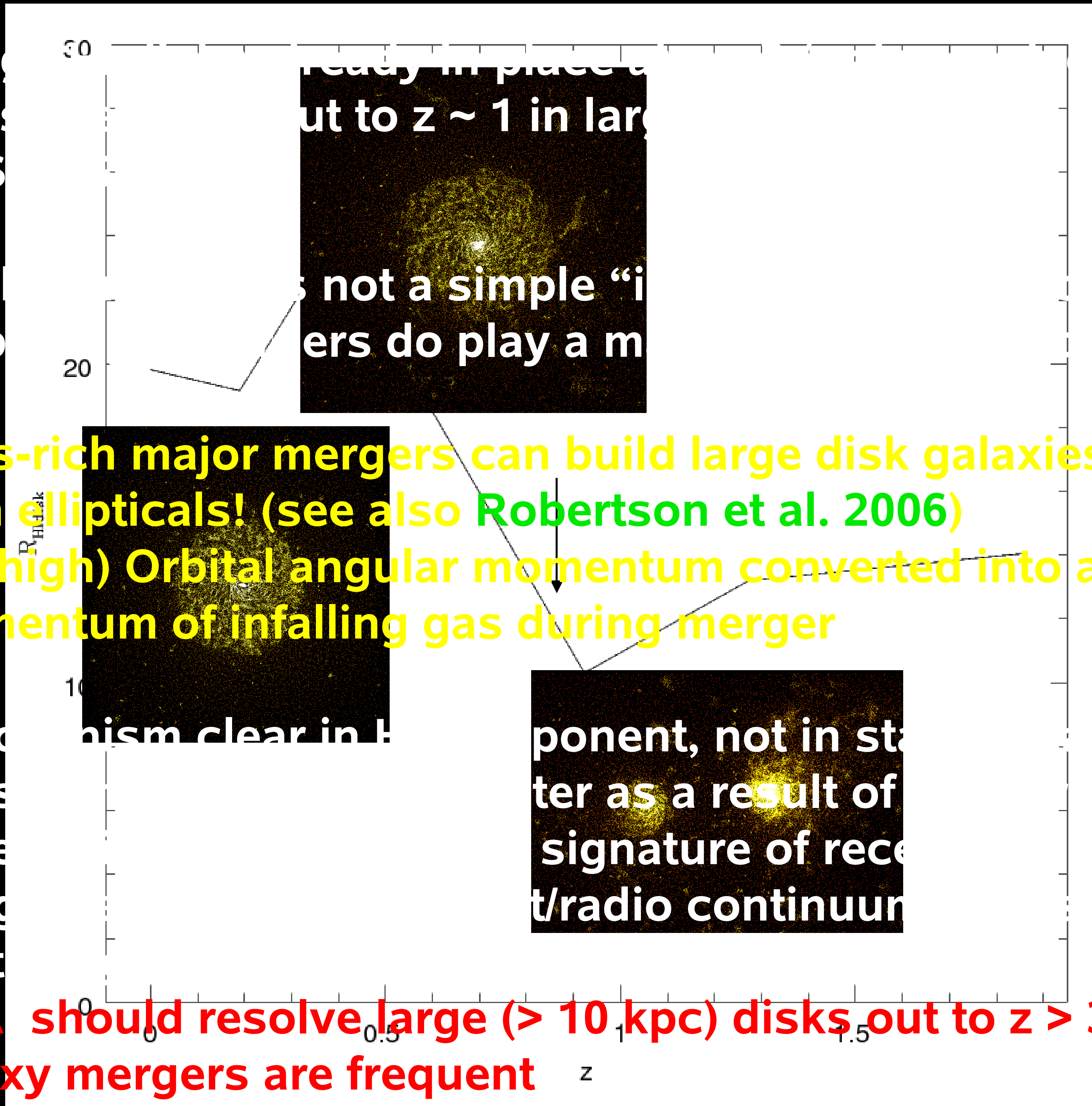


- Lar ready in place u d
disk ut to z ~ 1 in lar .g.
COS

- Disl s not a simple "i n;
surp ers do play a m wth

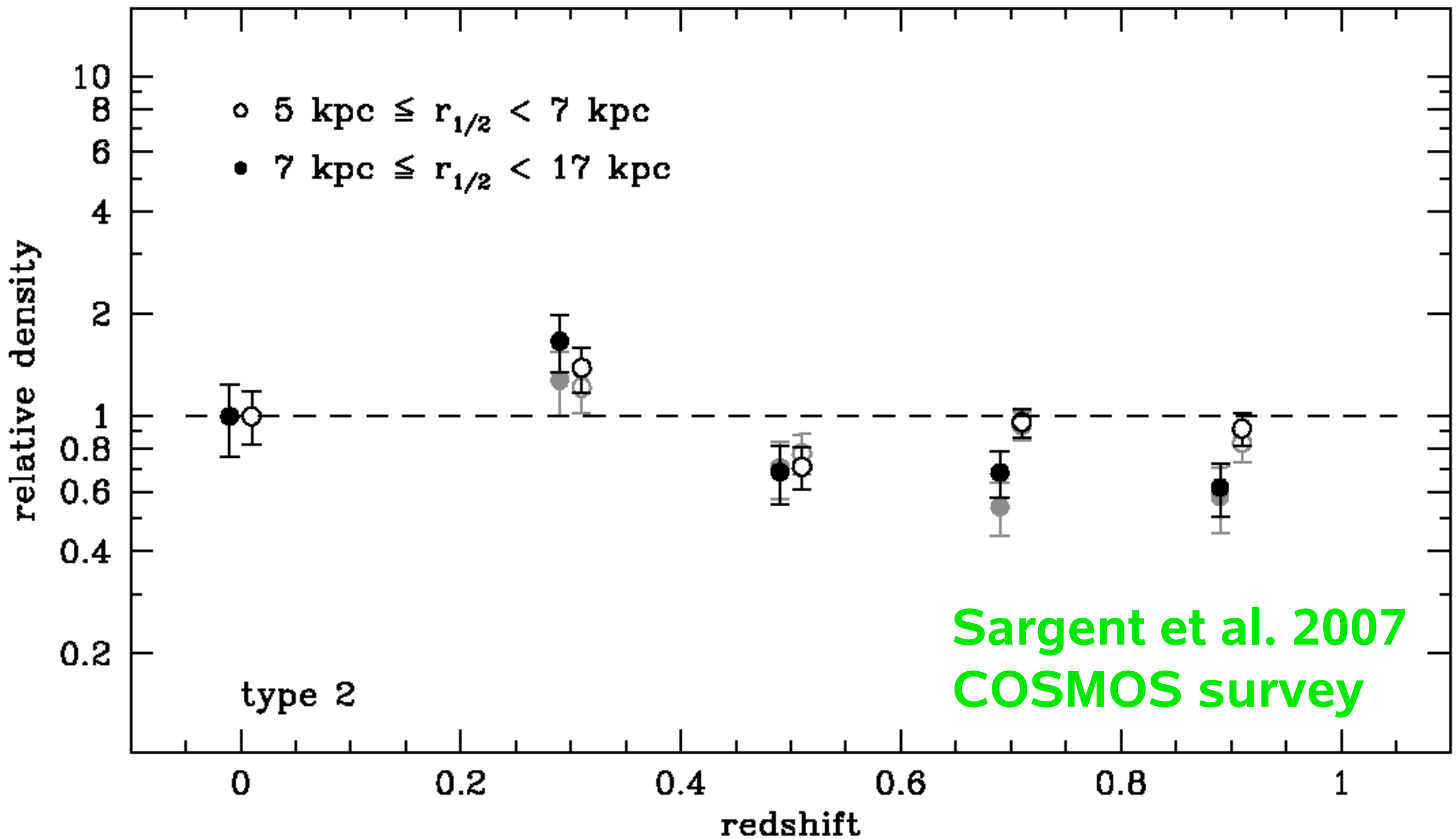
- Gas-rich major mergers can build large disk galaxies rather than ellipticals! (see also Robertson et al. 2006)
-→ (high) Orbital angular momentum converted into angular momentum of infalling gas during merger

- Mec hism clear in H ponent, not in st use new
stars ter as a result of ---→ HI
obse signature of rece
merg t/radio continuum if these
host



SKA should resolve large (> 10 kpc) disks out to z > 3 when galaxy mergers are frequent

EVOLUTION OF OPTICAL DISK SIZE



A deep, large SKA HI survey should measure HI disk size evolution for massive spirals over a redshift range > current optical surveys

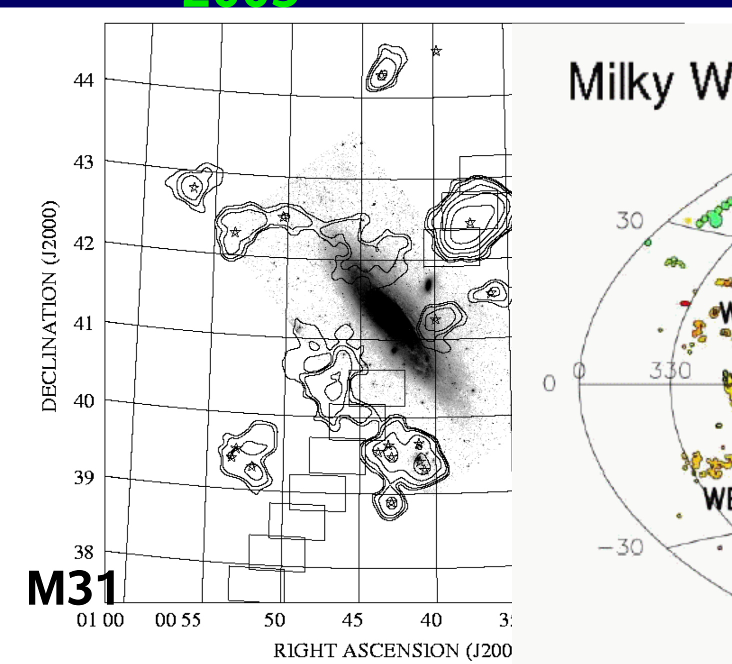
-→ more direct tracer of disk formation (HI comes before stars and is where the angular momentum is originally stored)

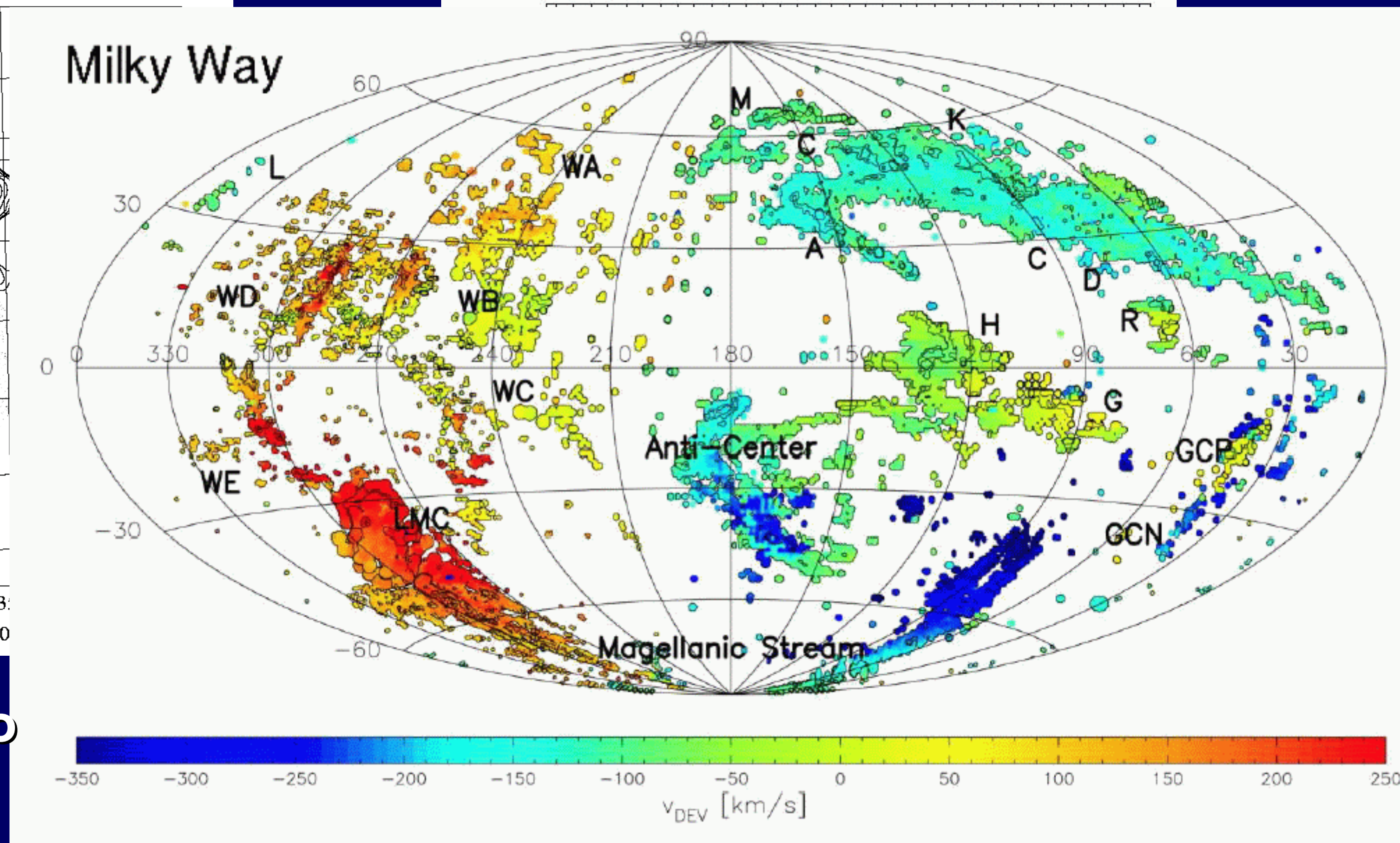
--→ ideal test for new generation of cosmological simulations

Galactic HVCs, HI clouds and extraplanar gas: Evidence for clumpy gas accretion at z=0?

Thilker et al. 2003

Grossi et al. 2008 (ALFALFA survey))



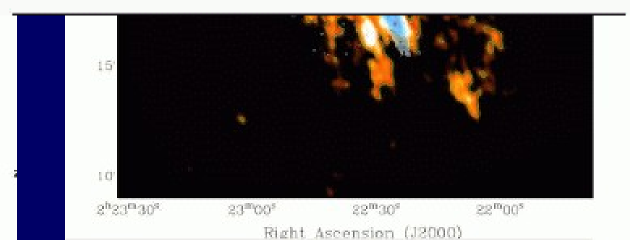


- Mgas~ 10^6 - 10^9 Mo
- size of structures: < 1 kpc to > 10 kpc

small local sample

-→ need large sample at z=0 an z > 0 -→ SKA

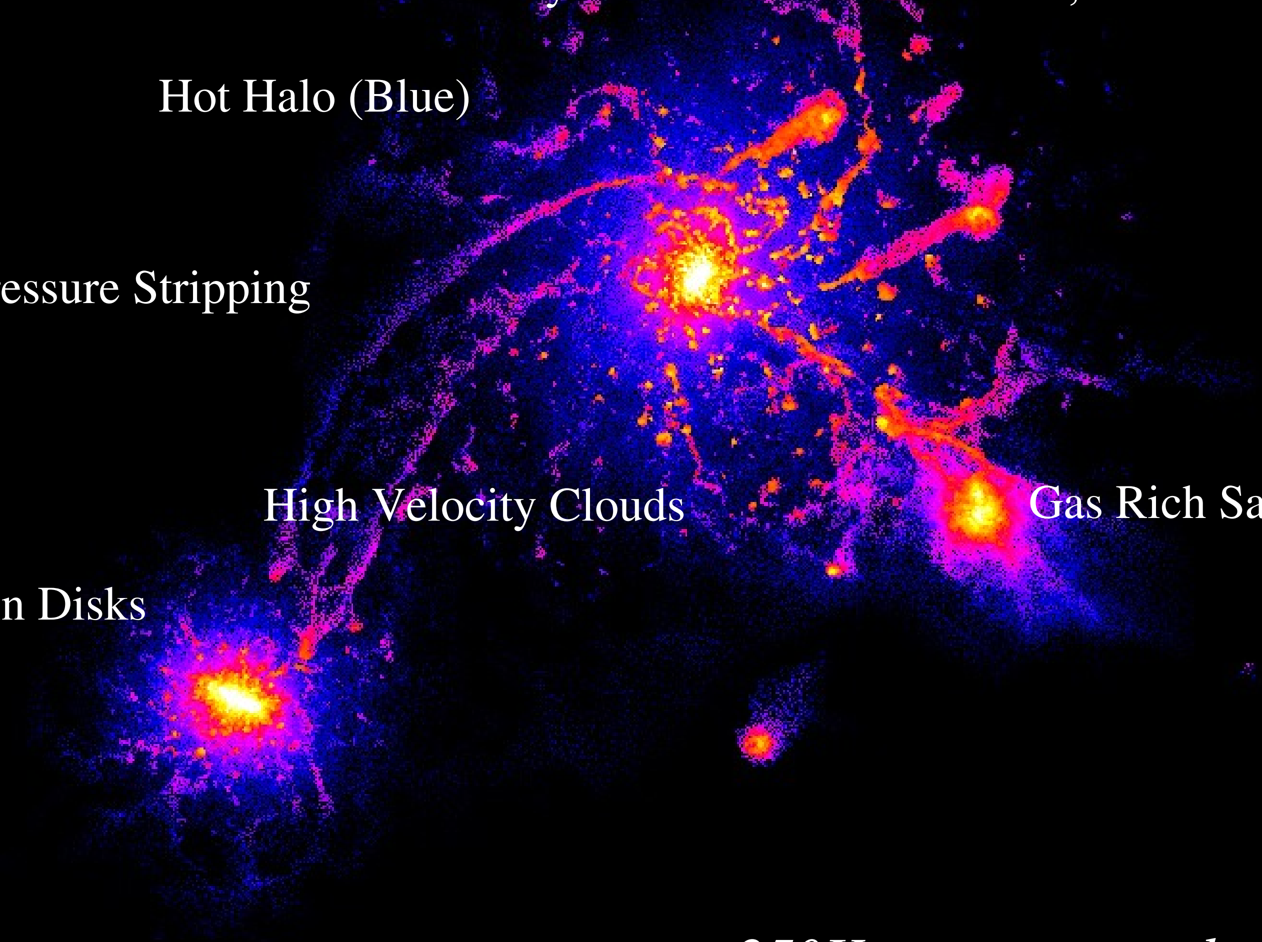
Fraternali et al. 2004



Structure of the ISM/IGM at z= 0.5

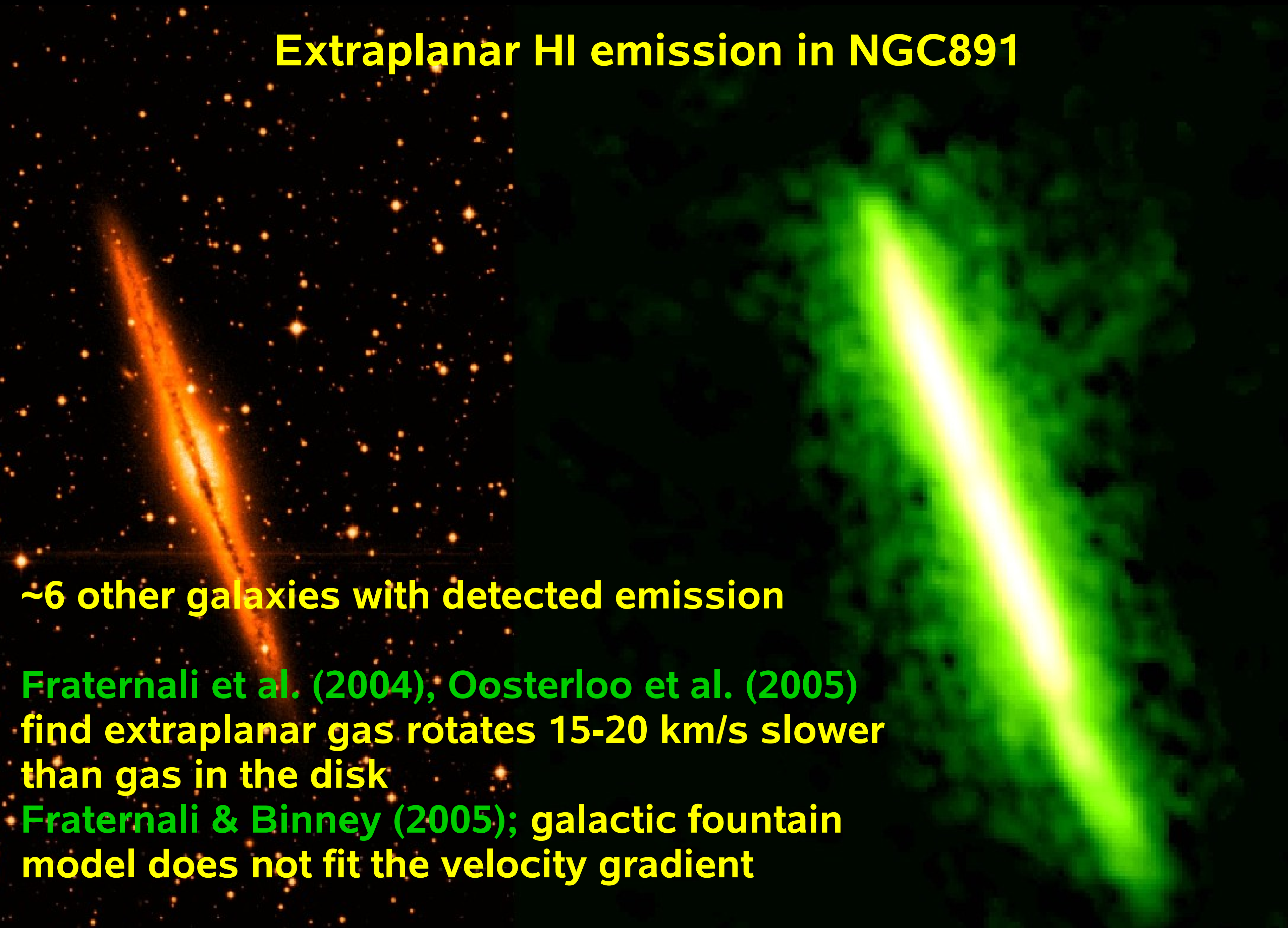
Lots of structure in cold (<~10^4 K) gas as tracer of galaxy formation

Gas clouds/structure well resolved only down to 10^6 solar masses, resolution 0.3Kpc



250Kpc across resolution 0.3Kpc

Extraplanar HI emission in NGC891



~6 other galaxies with detected emission

Fraternali et al. (2004), Oosterloo et al. (2005) find extraplanar gas rotates 15-20 km/s slower than gas in the disk

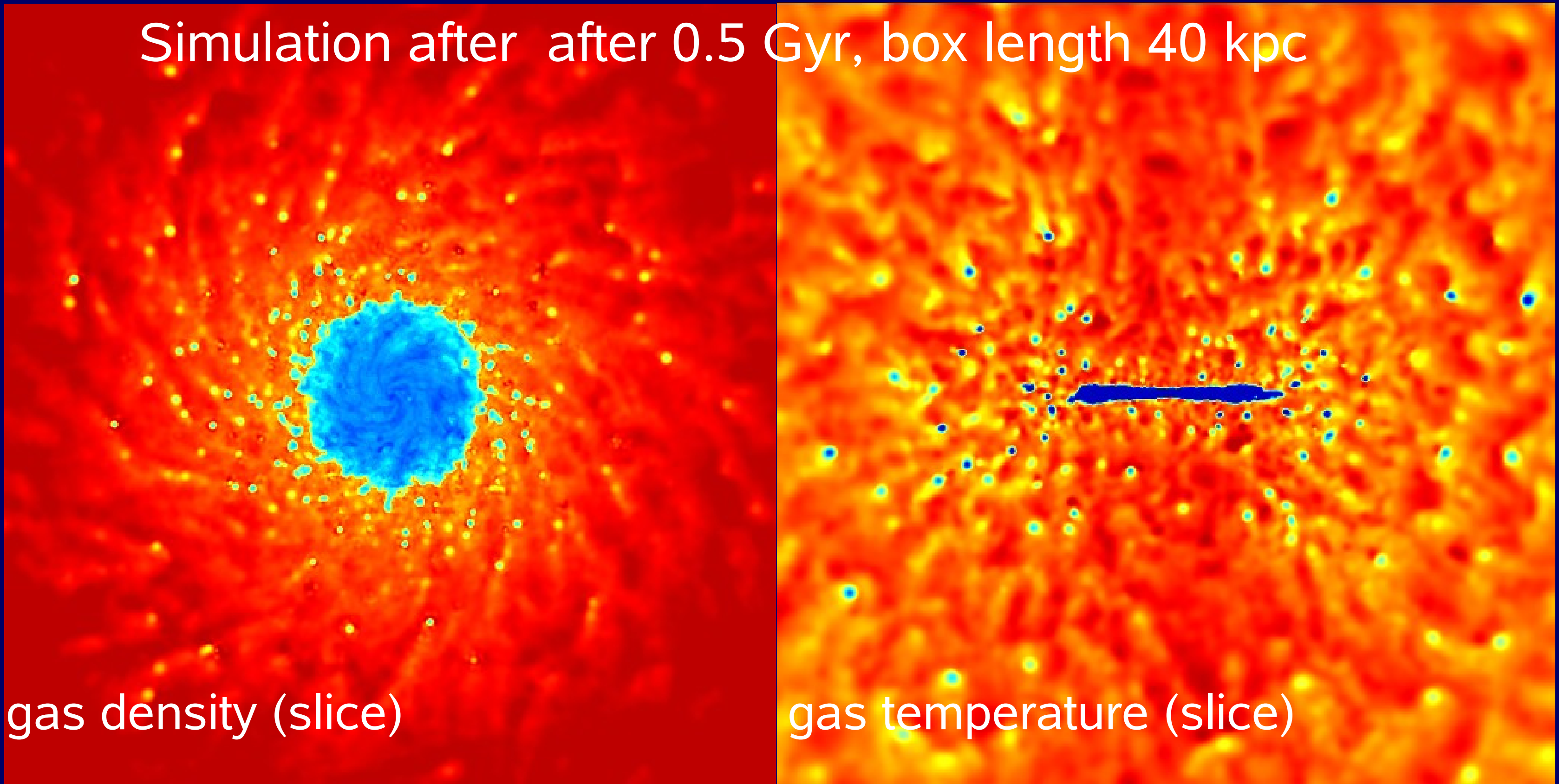
Fraternali & Binney (2005); galactic fountain model does not fit the velocity gradient

Cold pressure supported clouds in cooling hot halos via thermal instability: isolated collapse simulations

- Mcloud ~ 10^5- 10^6 Mo. At hi-res (Mgas ~ 10^3 Mo) clumps contribute 10% of the mass to disk, seen out to 3 times Rdisk (~ 50 kpc)
- Associated accretion rate < 0.1 Mo/yr i.e. < SFR.Most of accretion is smooth rather than clumpy
- Clouds have high velocities, 100-200 km/s – relation with HVCs?

to answer need to know of much gas ionized and how much HI in clumps.
-→ Need to improve treatment of radiation physics (add cooling by metals, UV bg (Kaufmann et al. 2008)

Kaufmann, Mayer et al. 2006

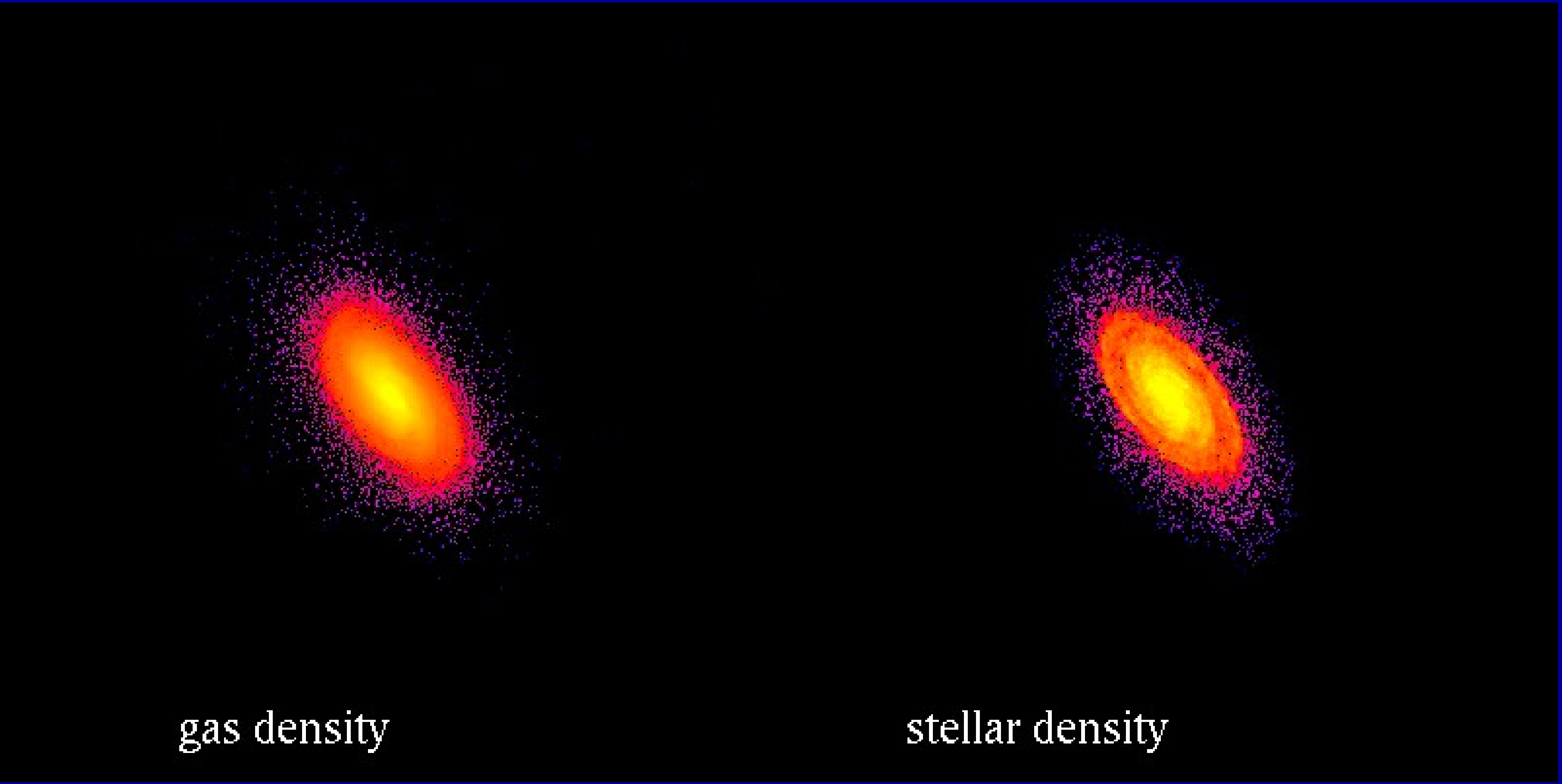


Dwarf satellites of bright galaxies: Gas stripping by tides+ram pressure

"big dwarf"' – Vpeak= 60 km/s (M/L~ 30) - Mass ~ NGC205 (bright M31 satellite)

Hot corona density: ρ_{max} ~ 10^{-4} atoms/cm^3 (cfr. Sembach et al. 2003, 2004)

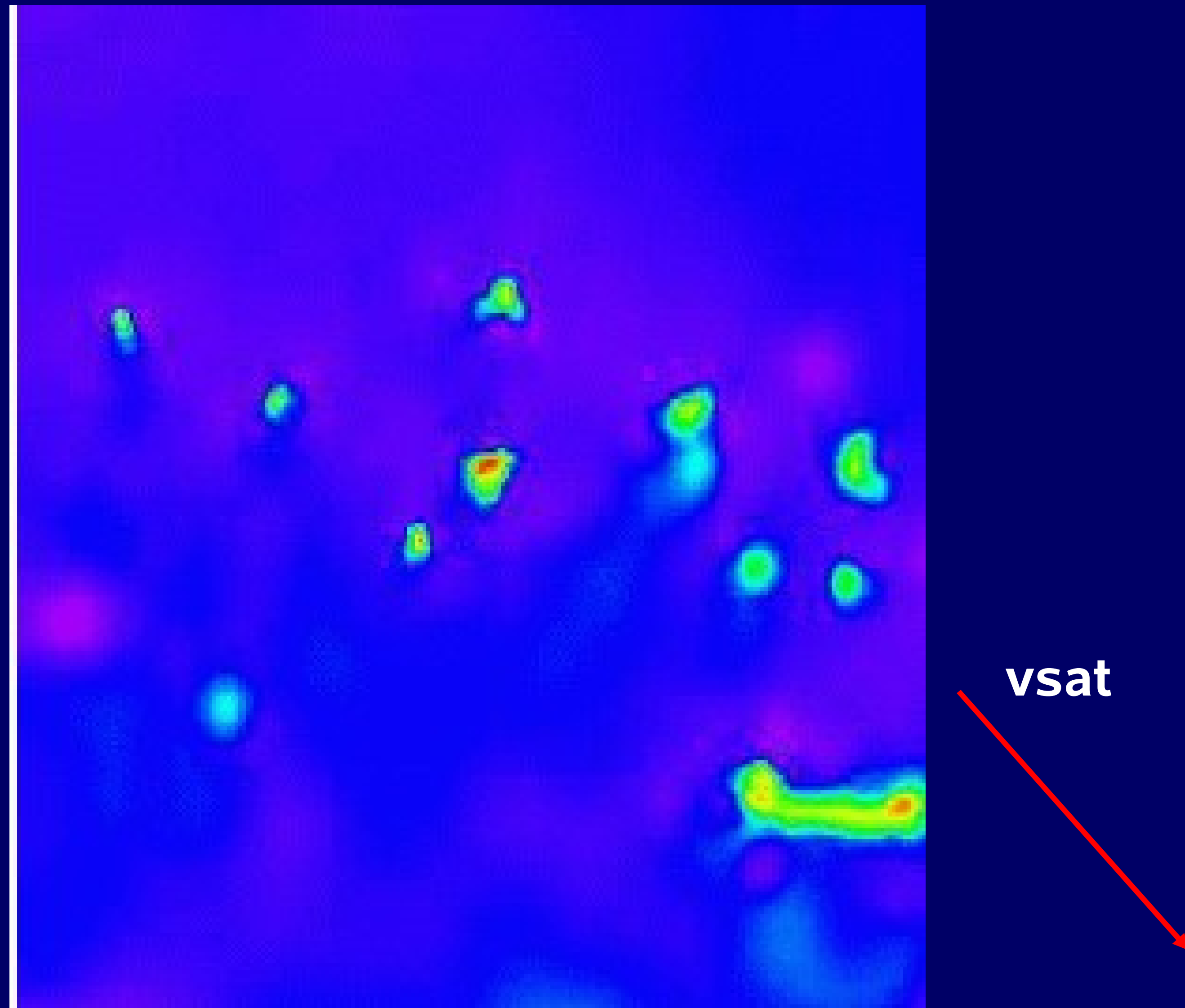
Apocenter = 250 kpc, Pericenter= 50 kpc (typical cosmological orbit)



Mayer et al. 2006, 2007

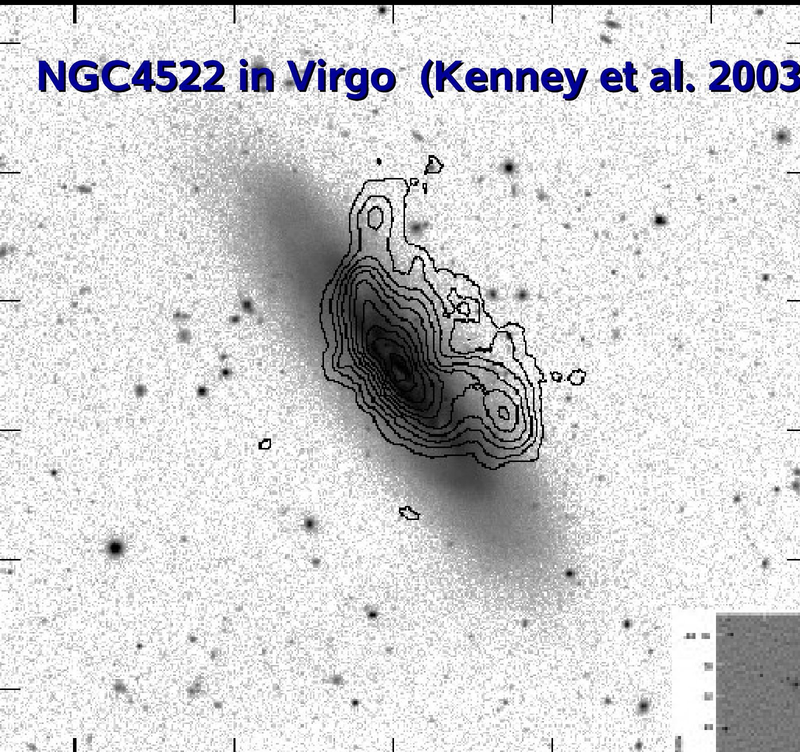
Cold (T~ 10^4 K) pressure confined clouds and filaments, mass 10^4-10
Mo from thermal instability in the ram pressure tail of the satellite.
Have high velocities (~ v_{sat}~ 200 km/s), sink towards primary by ram pressure drag in ~ 10^8 years

n_{HI} ~10^{19}-10^{20} cm^{-2}

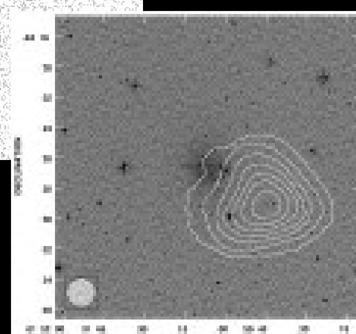


Mayer et al. 2006

But for dwarf galaxy satellites in groups no clear evidence of stripping by tides/ram pressure



NGC4522 in Virgo (Kenney et al. 2003)



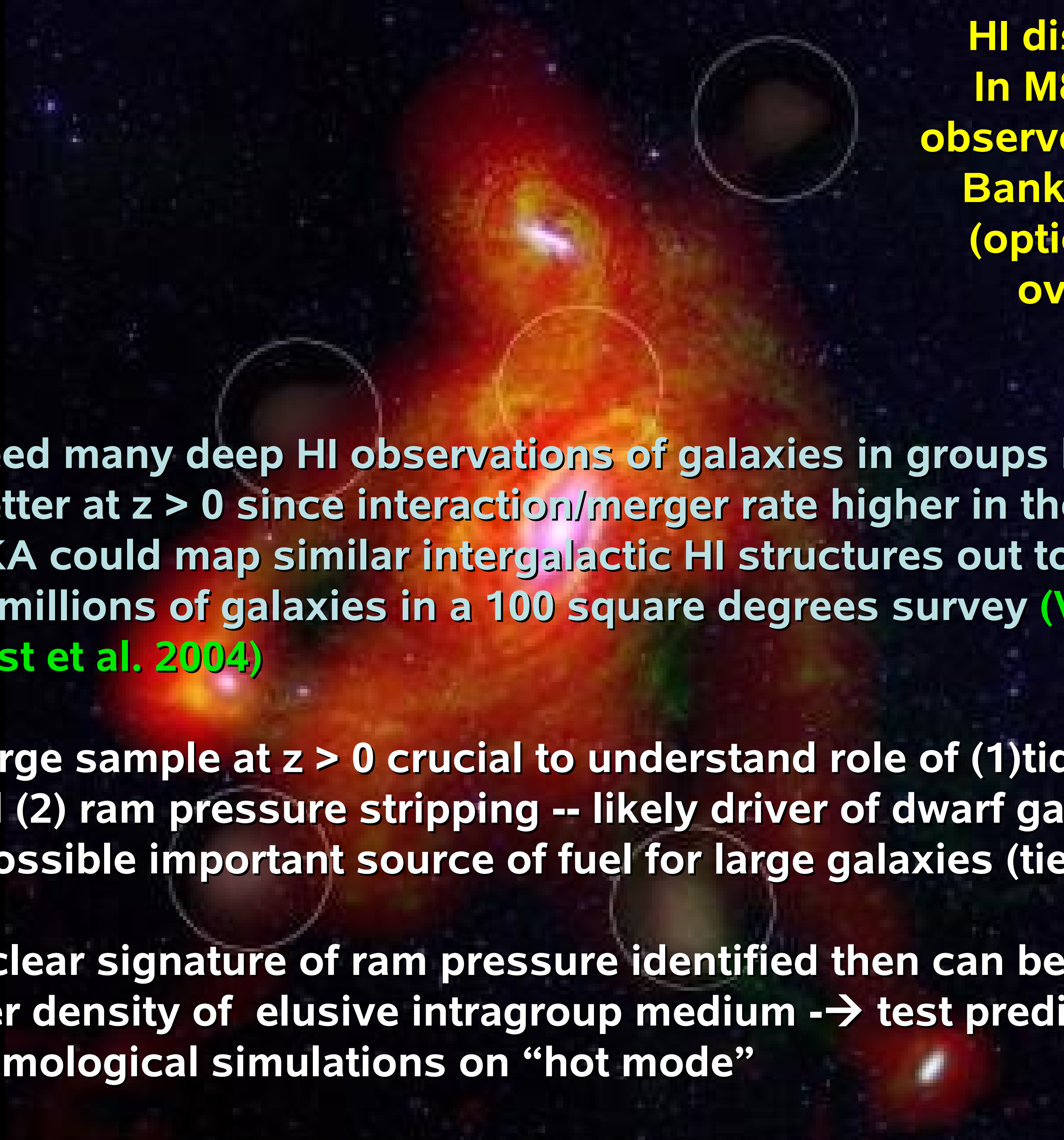
Phoenix,LG dwarf

However:

(2) Gas has low density in dwarfs, 10^{19-20} cm-^{2} will become even lower as it is stripped --→ deep HI imaging

(2)Most dwarf satellites in groups at z=0 are dwarf spheroidals (no gas). Models predict progenitors of bright dSphs (Mb ~ -13) were SMC-size disky dwarfs (Mb ~ -16) that lost gas at z ~ 0.5-1 (Mayer et al. 2006 ;2007)

Need deep HI observations at z > 0 to reveal gas stripping of dwarfs in groups



HI distribution
In M81 group
observed by Green
Bank Telescop
(optical image
overlaid)

- Need many deep HI observations of galaxies in groups like this.
- Better at z > 0 since interaction/merger rate higher in the past
- SKA could map similar intergalactic HI structures out to z ~0.2 for millions of galaxies in a 100 square degrees survey (Van der Hulst et al. 2004)

- Large sample at z > 0 crucial to understand role of (1)tidal interactions and (2) ram pressure stripping -- likely driver of dwarf galaxy evolution + possible important source of fuel for large galaxies (ties with accretion)

- If clear signature of ram pressure identified then can be used to infer density of elusive intragroup medium -→ test prediction of cosmological simulations on “hot mode”

CONCLUSIONS

- Numerical simulations of (disk) galaxy formation in the LCDM framework are finally producing realistic disk galaxies

- They produce a wealth of information on the evolution and structure of the cold HI component ---→ high potential for synergy with SKA

- SKA should help answering several key questions of galaxy formation and evolution:

- *How does the gas get to galaxies (cold vs. hot accretion)?*
- *How does the HI disk of galaxies evolve with redshift?*
- *What is the role of mergers in building the disk?*
- *Are HVCs and other cold HI structures observed locally the result of on-going accretion?*
- *What is the typical gas accretion rate of galaxies?*
- *Are tidal interactions and ram pressure the main drivers of galaxy transformation in groups ($M_* \sim 10^{13}$ Mo today)?*

GADGET-2, No Feedback

Naab et al Apj 07

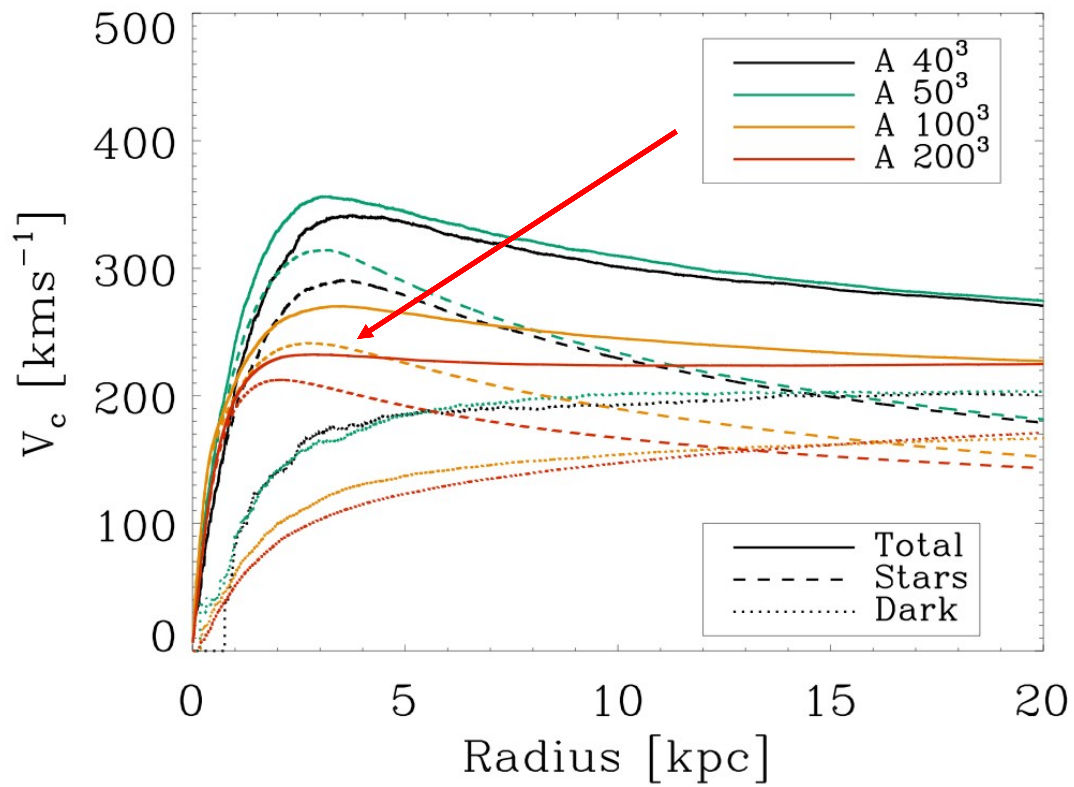
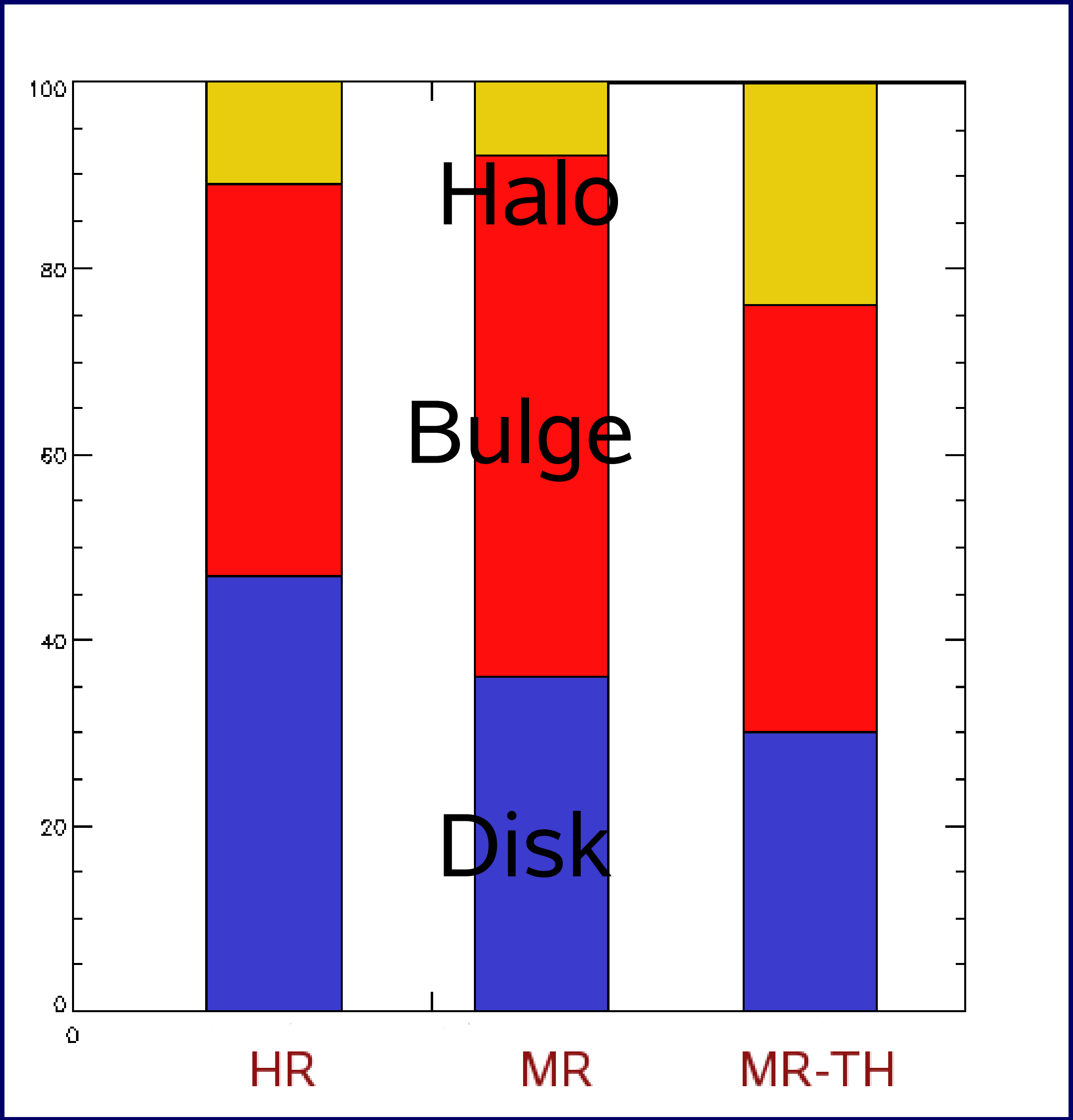


FIG. 1.— Circular velocity curves for galaxy A at four different numerical resolutions: 40^3, 50^3, 100^3, and 200^3 SPH particles and collisionless dark matter particles, respectively. Note how the rotation curves become increasingly flat as the resolution increases.

Peak Vel
decreases 30%
as mass
resolution
Increases
125 fold.

SN Feedback and Galaxy Components In L* Galaxies. Kinematic Decomposition.



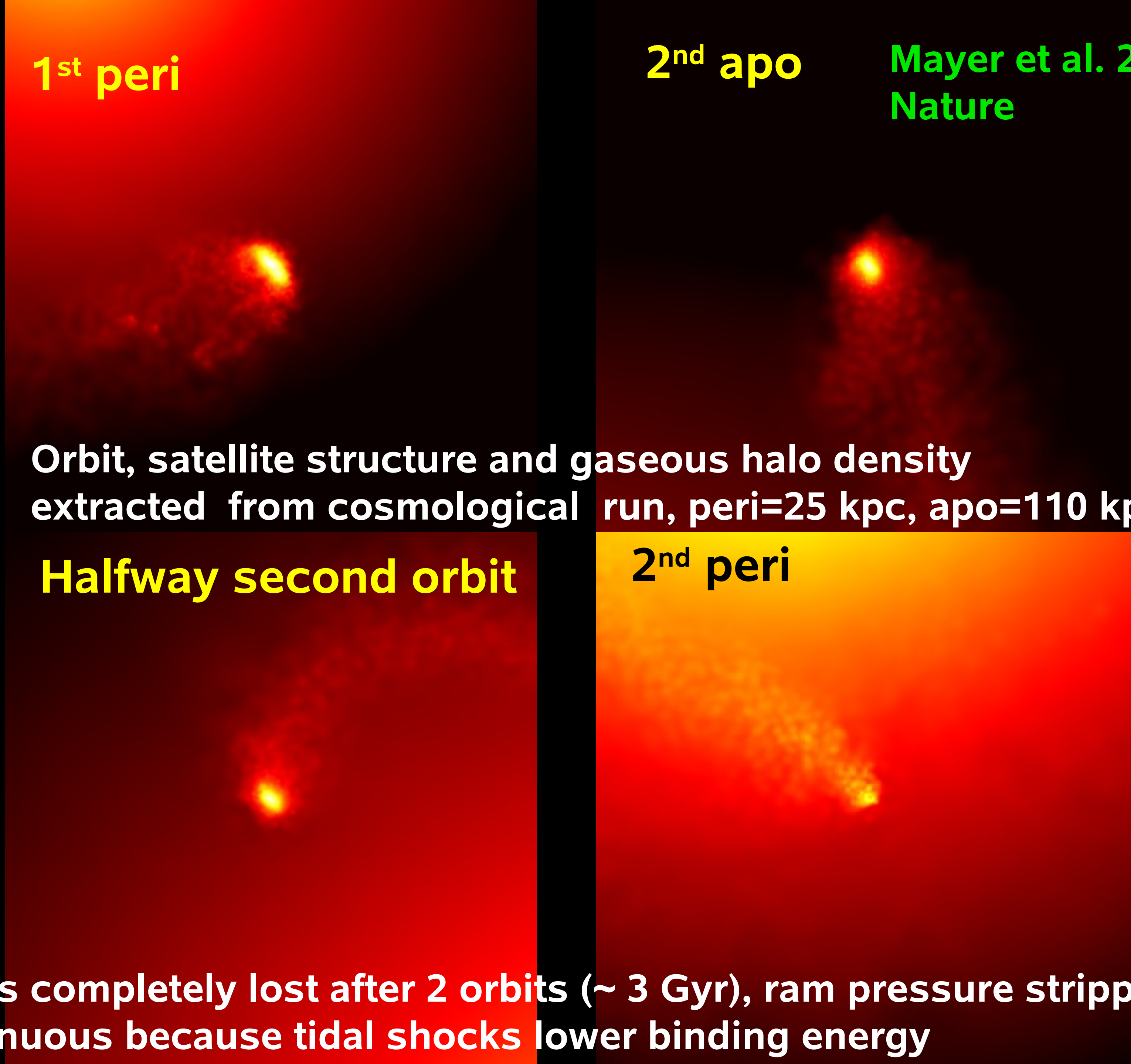
Effect of increasing resolution:

-- Stellar Halo less massive.

-- Disk more Massive.

-- Bulge less massive

***Caveat*: cannot produce bulge-less disk galaxies yet.**



Mayer et al. 2007, Nature

Orbit, satellite structure and gaseous halo density extracted from cosmological run, peri=25 kpc, apo=110 kpc

Gas is completely lost after 2 orbits (~ 3 Gyr), ram pressure stripping continuous because tidal shocks lower binding energy

“Downsizing” of galaxy population
At odds with hierarchical structure formation?

Observations show low mass galaxies on average younger than high mass galaxies (from ages of stars)

Effects of Increasing Resolution

Rotation curves get flatter = mass distribution more realistic (central baryon concentration decreases)

10 Catinella et al.

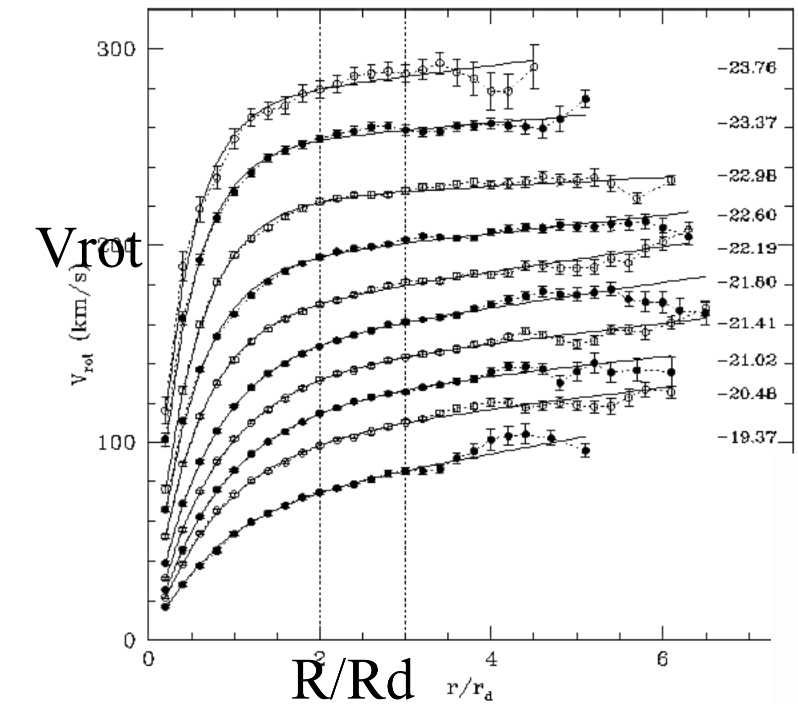
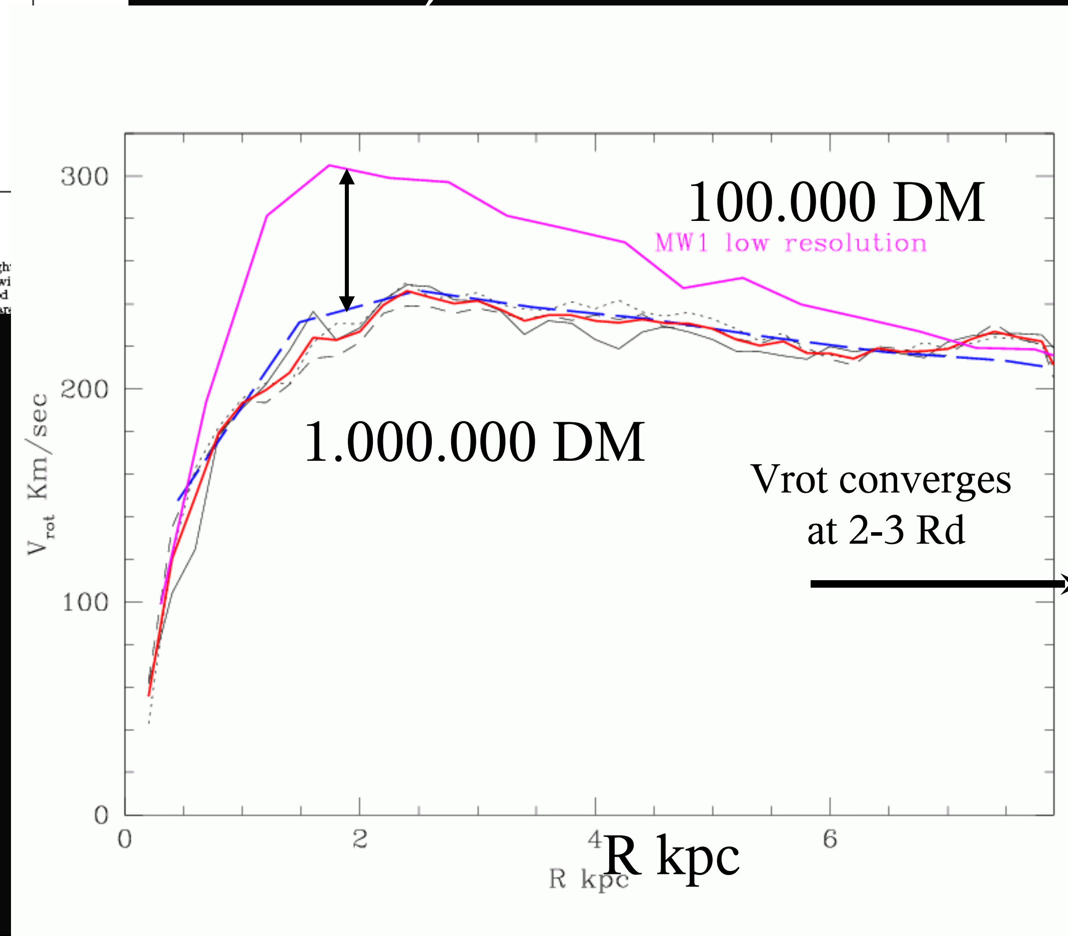


FIG. 1.— Template RCs parameterized as functions of exponential disk scale lengths. Each curve is labeled on the righ
I-band absolute magnitude ($H_0 = 70$ km s^{-1} Mpc^{-1}). The final sample includes 2155 RCs extending beyond 2 r_d, and wi
to the line of sight $i < 80°$. The vertical, dotted lines show the interval over which the velocity normalization was performed
error bars are Poissonian errors on the mean. Polyex fits to the data points are indicated by solid lines; the fit coefficients ar



Cosmology and Hydrodyamics with Gasoline

Conspirators:

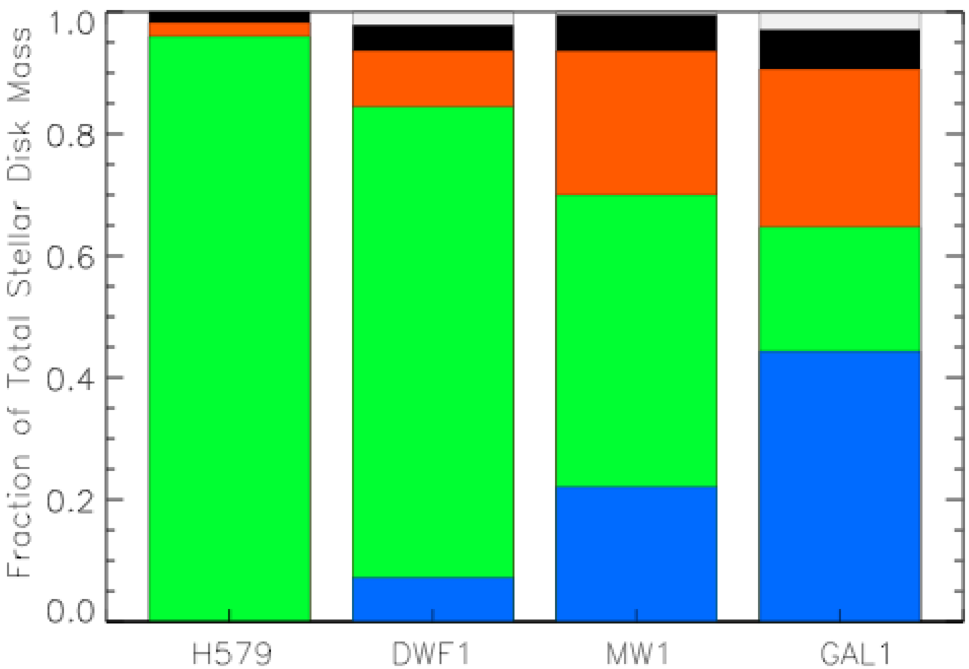
James Wadsley	McMaster Univ.
Joachim Stadel	Univ. Zurich
Tom Quinn	Univ. Washington
Lucio Mayer	Uni/ETH Zurich
Ben Moore	Univ. Zurich
Fabio Governato	Univ. of Washington
Stelios Kazantzidis	KIPAC Stanford
Derek Richardson	Univ. of Maryland
George Lake	Univ. of Zurich

Multi Platform, Massively Parallel treecode + SPH, multi stepping, cooling, UV background, Star Formation, SN feedback, radiative transfer. Several state-of-the art calculations published in cosmological structure formation, galaxy formation, planet formation, Solar System dynamics (for code description see Wadsley,Stadel & Quinn 2004).

Gas Accretion modes in hi-res cosmological simulations

Contribution to disk stars at z=0

satellites cold flows shocked



Halo Mass: 4e10 2e11 1e12 3e12

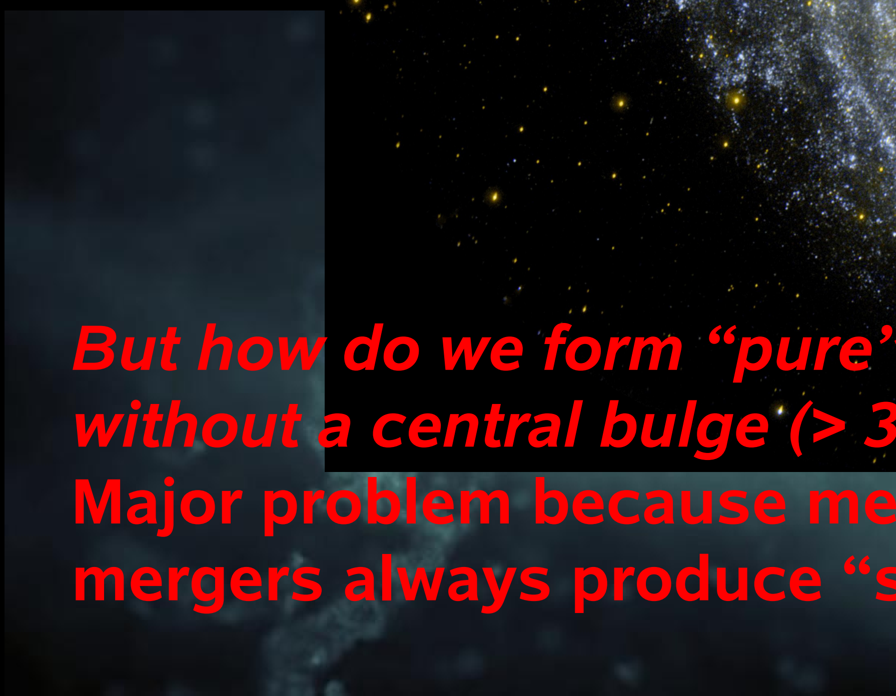
Cold flows includes both accretion of large-scale filaments and clouds produced by thermal instability (barely resolved)

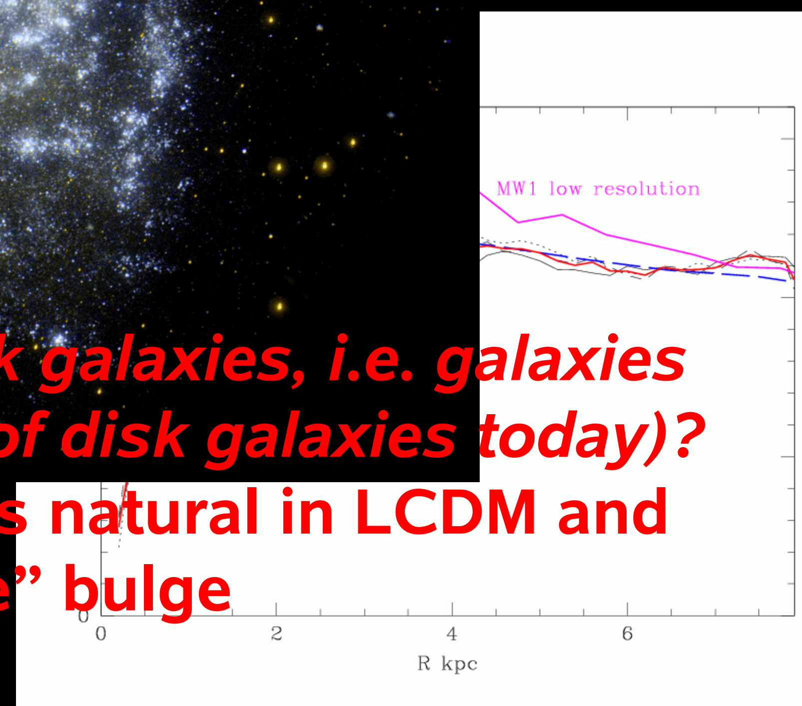
Low-mass galaxies (M33-LMC size) ideal testbed for cold Accretion --→ ideal target for future deep HI observatio

Brooks et al in prep.

Disk than we

Highe physics
are n laxies





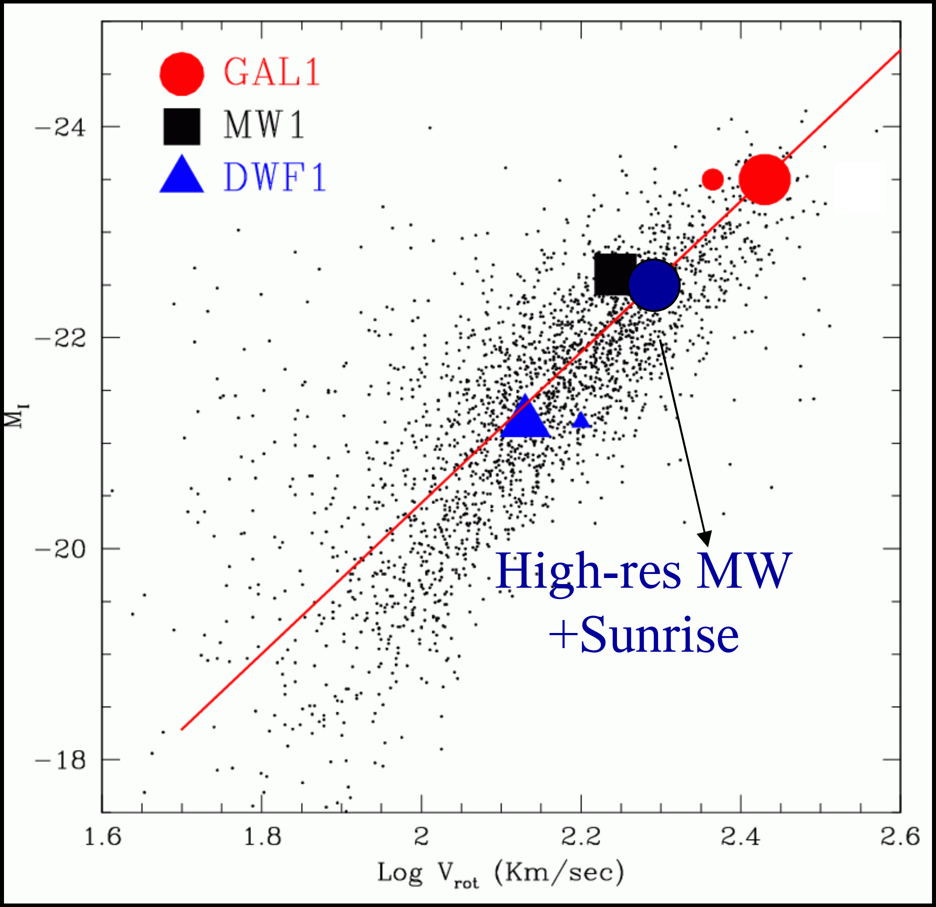
But how do we form "pure" disk galaxies, i.e. galaxies without a central bulge (> 30% of disk galaxies today)?

Major problem because mergers natural in LCDM and mergers always produce "some" bulge

Lesson: if a rotationally supported disk forms (= baryons managed to preserve enough angular momentum) then it will be degraded into a thick, spheroidal mass distribution (more like a bulge) when resolution is not sufficient

But this does not fully address the issue of angular momentum catastrophe.

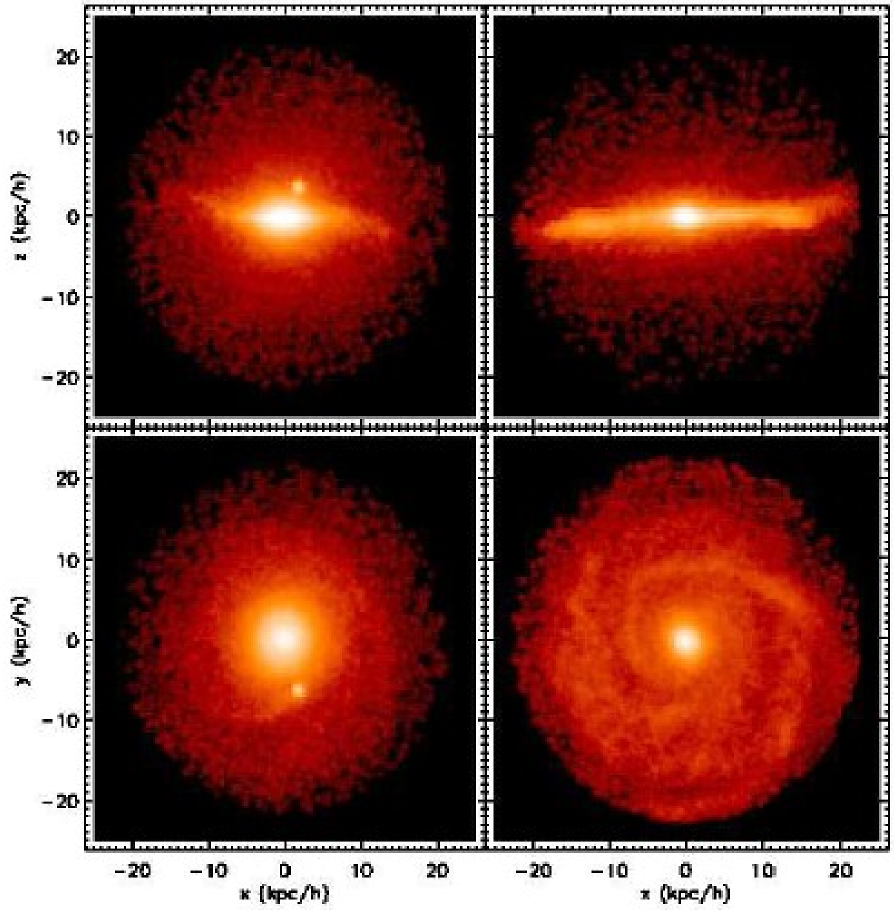
I band TF & baryonic TF



Data from Giovanelli & Haynes 05

Effects of Feedback. Zavala et al 08

No FB



FB on.

Baryon Distribution

Gas Fraction

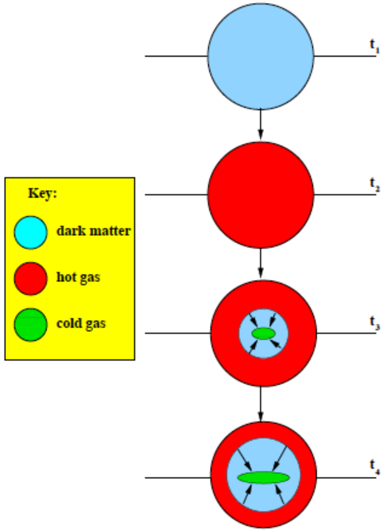
Small Galaxies: Feedback

L* : Star Form. +Feedback +Resolution

Galaxies>L* : SF+ Resolution

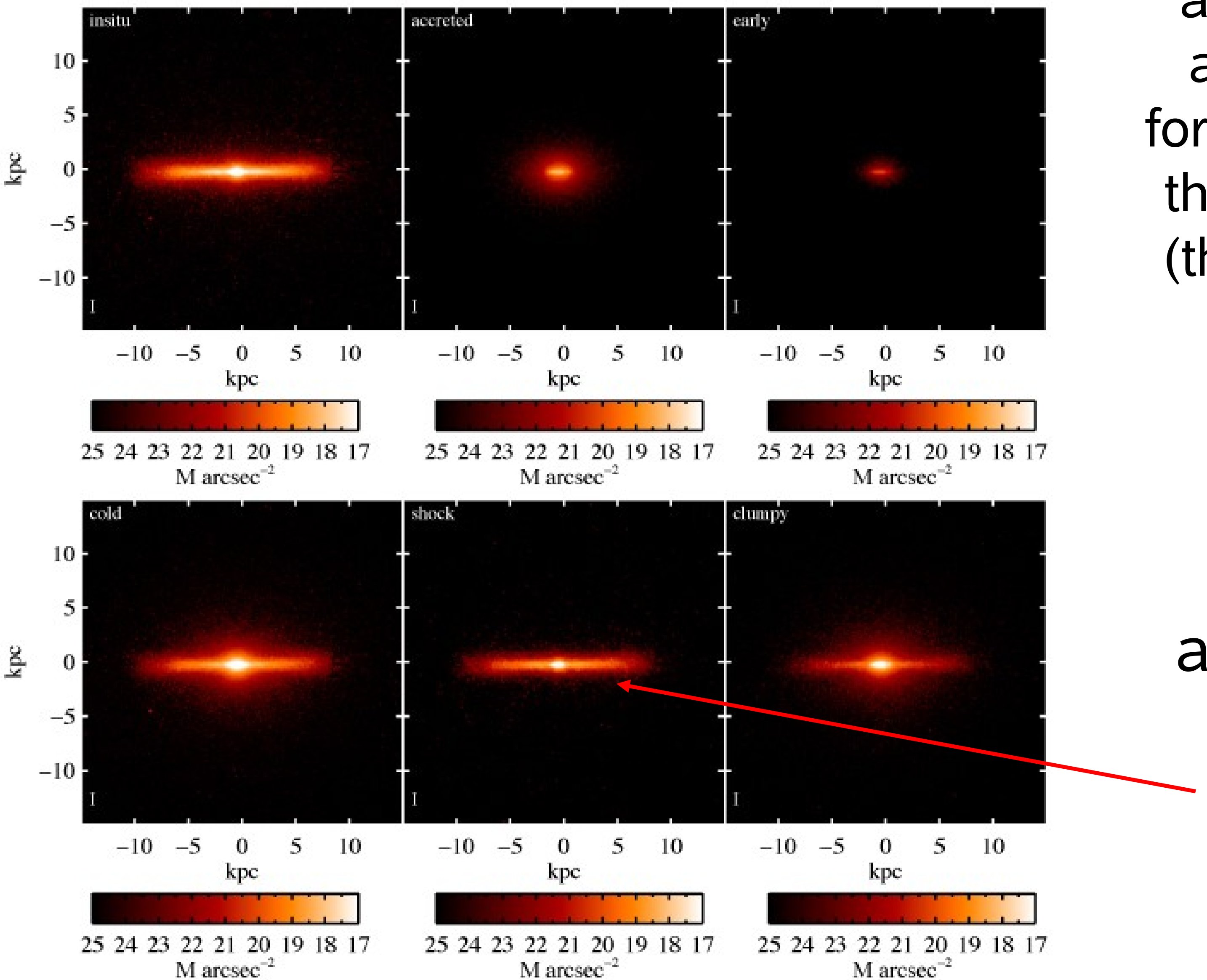
Vc

The Assembly of Galaxy Components: The Disk



Baugh et al 06

Accretion of different components in L* Galaxies

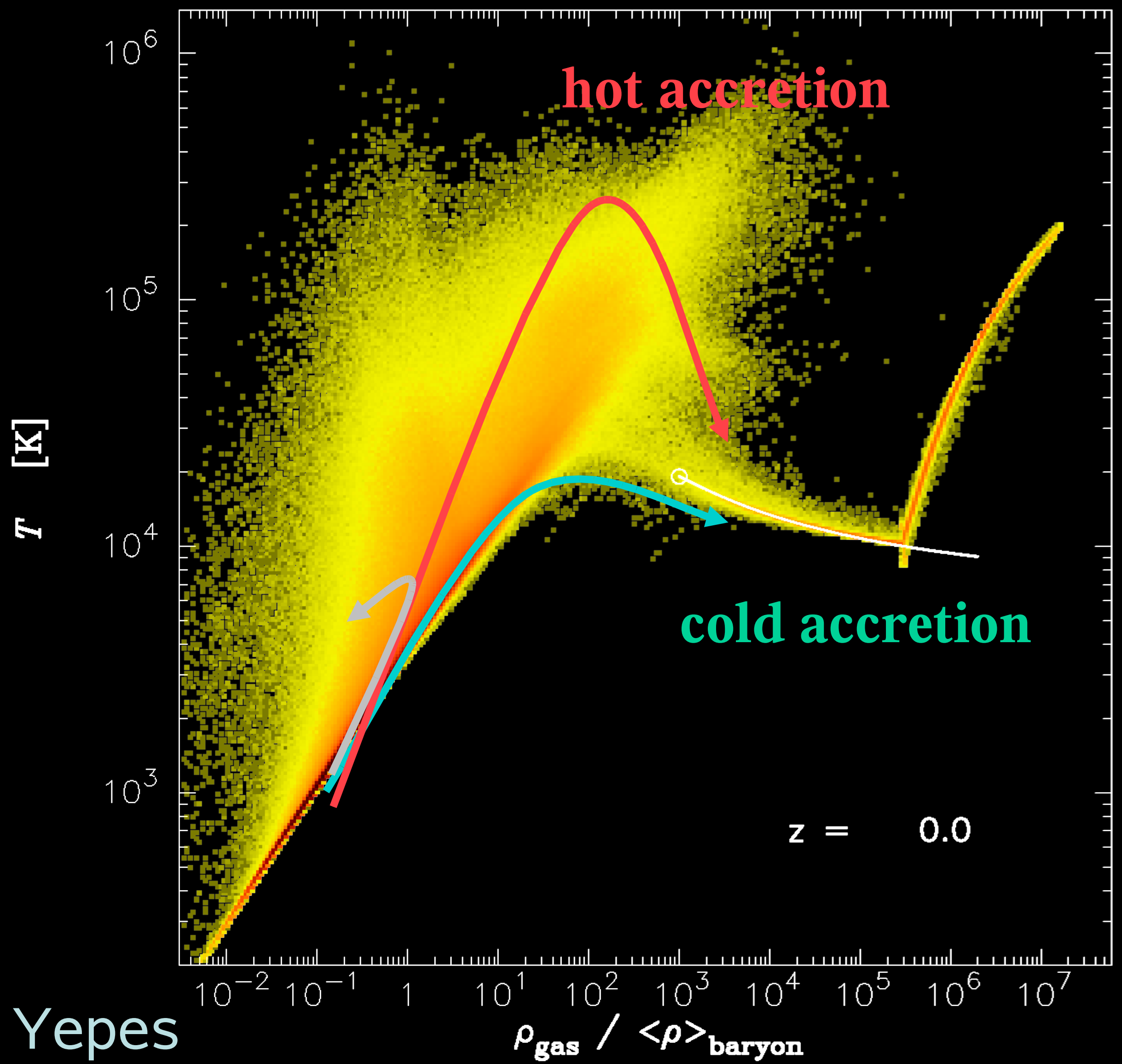


Stars accreted as stars form part of the bulge. (thick disk faint)

Late accretion forms disks

The New Model of Gas accretion: Cold Flows

"Cold mode"
(Keres et al. 05)
of galactic gas accretion:
gas creeps along the equilibrium line between heating and cooling. It never Shocks to Tvir.

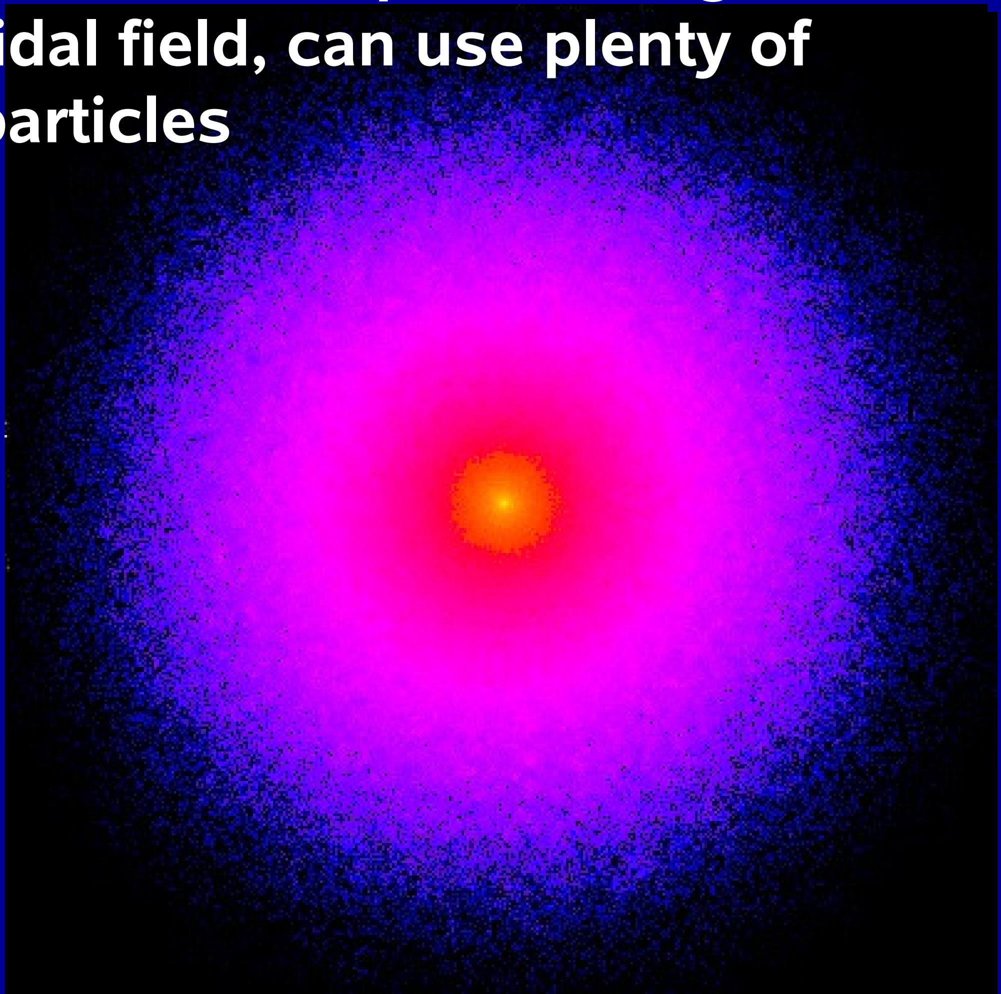


Courtesy of Hoeft & Yepes

“Quiescent” disk formation

Tobias Kaufmann, Lucio Mayer et al. (2005, 2006).

Isolated collapse, no large scale tidal field, can use plenty of particles



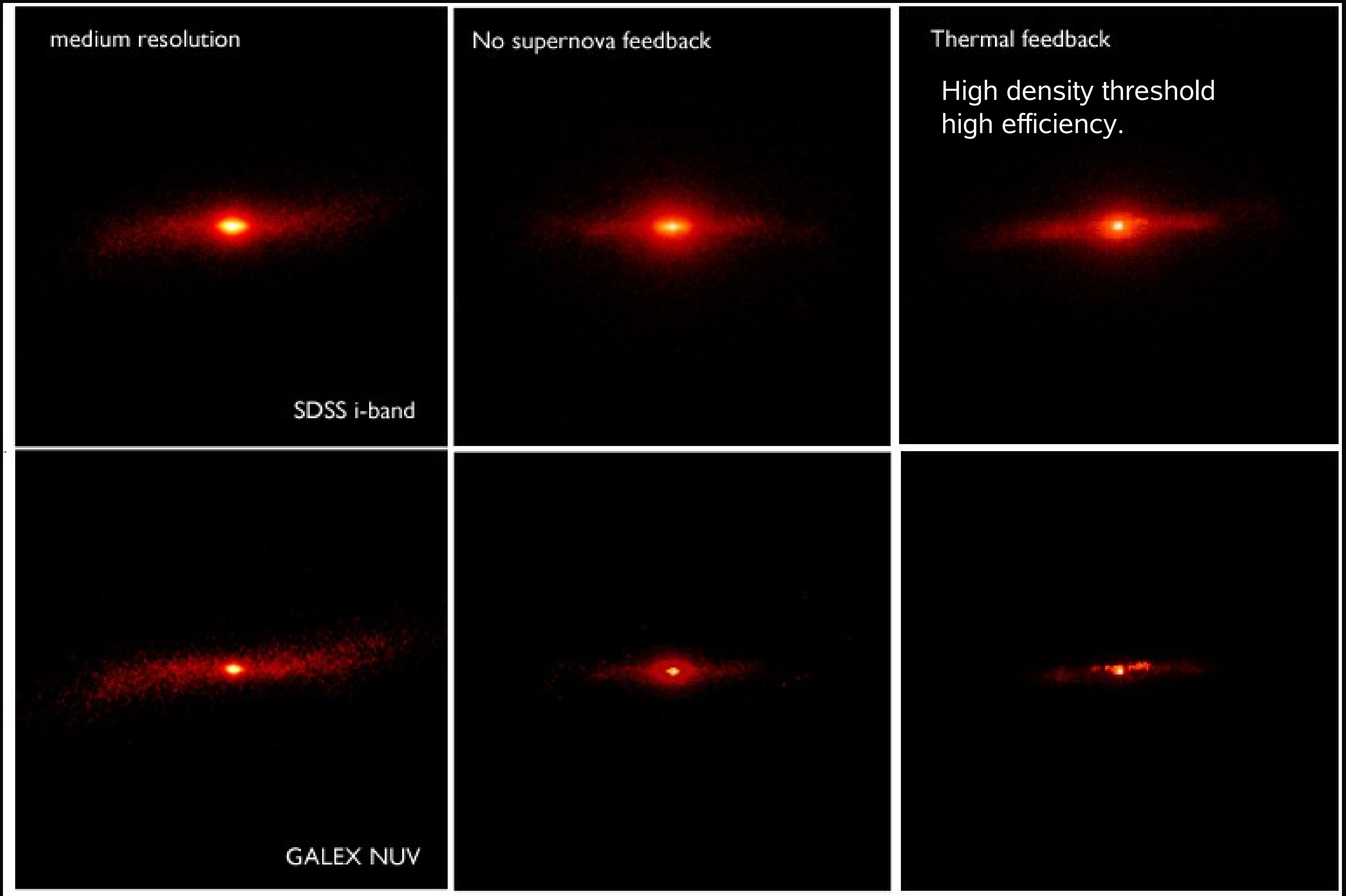
Dark matter halo with gas

Start from NFW halo with an embedded rotating hot gaseous halo in hydrostatic equilibrium. Similar to Mo, Mao & White initial conditions but fewer assumptions

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

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

Effects of Feedback and Alternative SF



II) Input physics

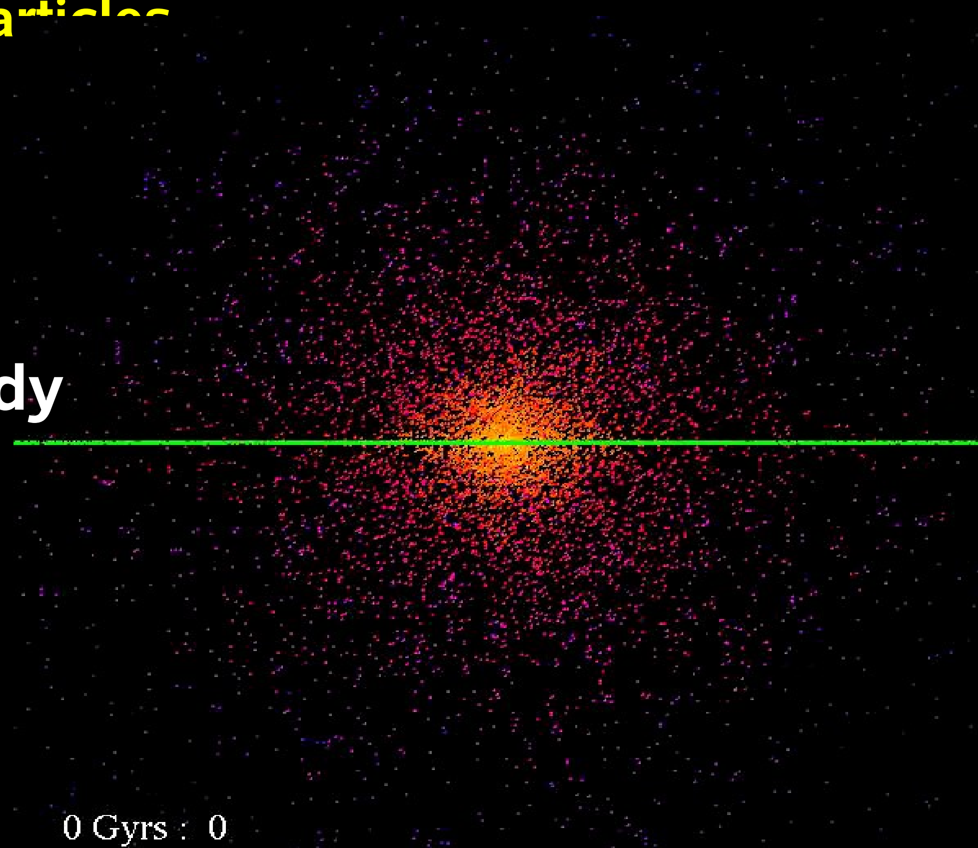
Numerical issue 1: artificial disk heating

Mayer 2004

Two-body gravitational scattering of stars and gas due to dark matter particles.

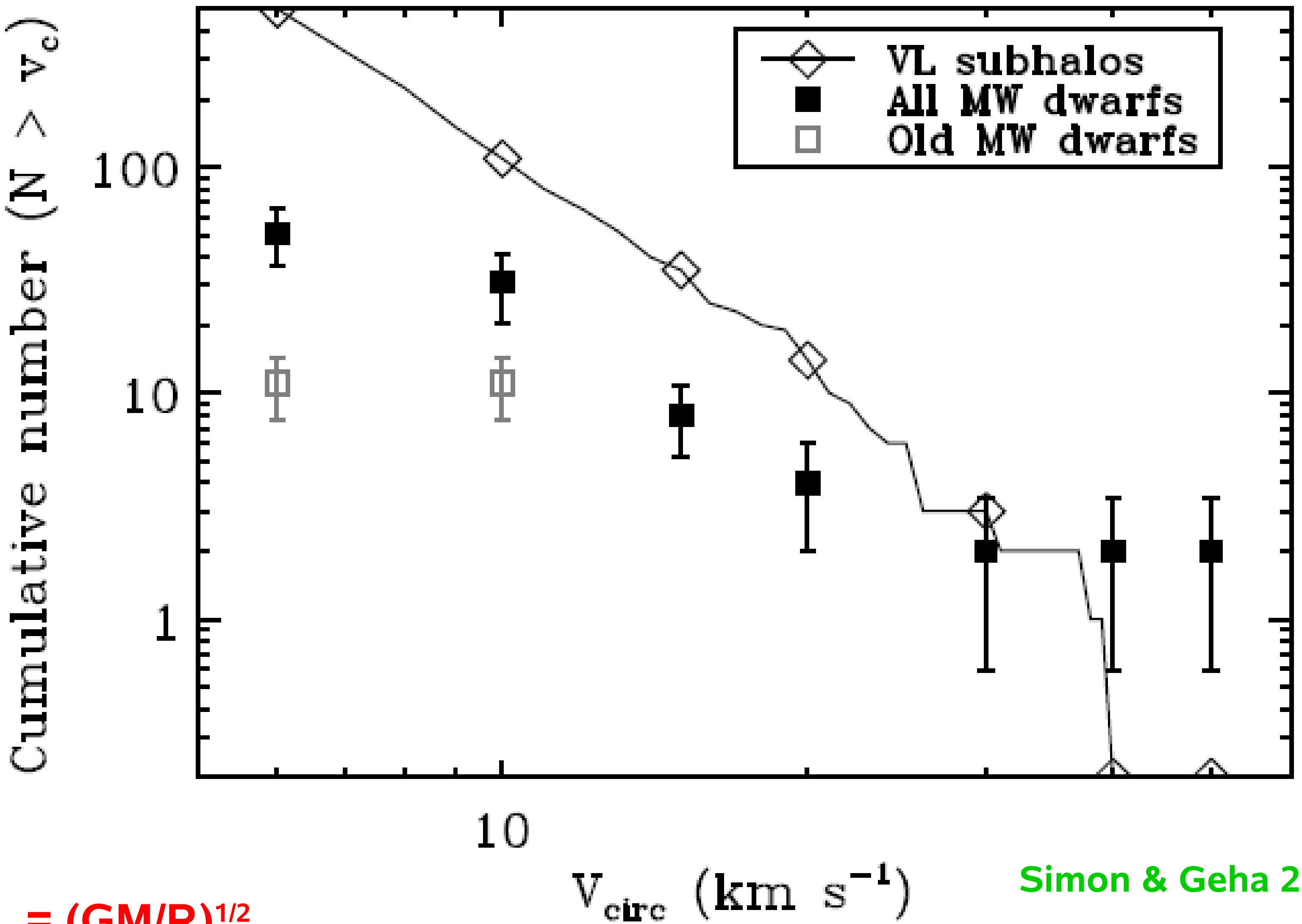
Occurs because one uses (too coarse) discrete representation of collisionless system (in principle should use large Np but limited by computing power)! ----> usually dark matter particles much heavier than stellar/gas pa

Need Ndm >= 10^5 for ΔE (due to two-body encounters) << E_{bind} (gravitational binding energy of disk)



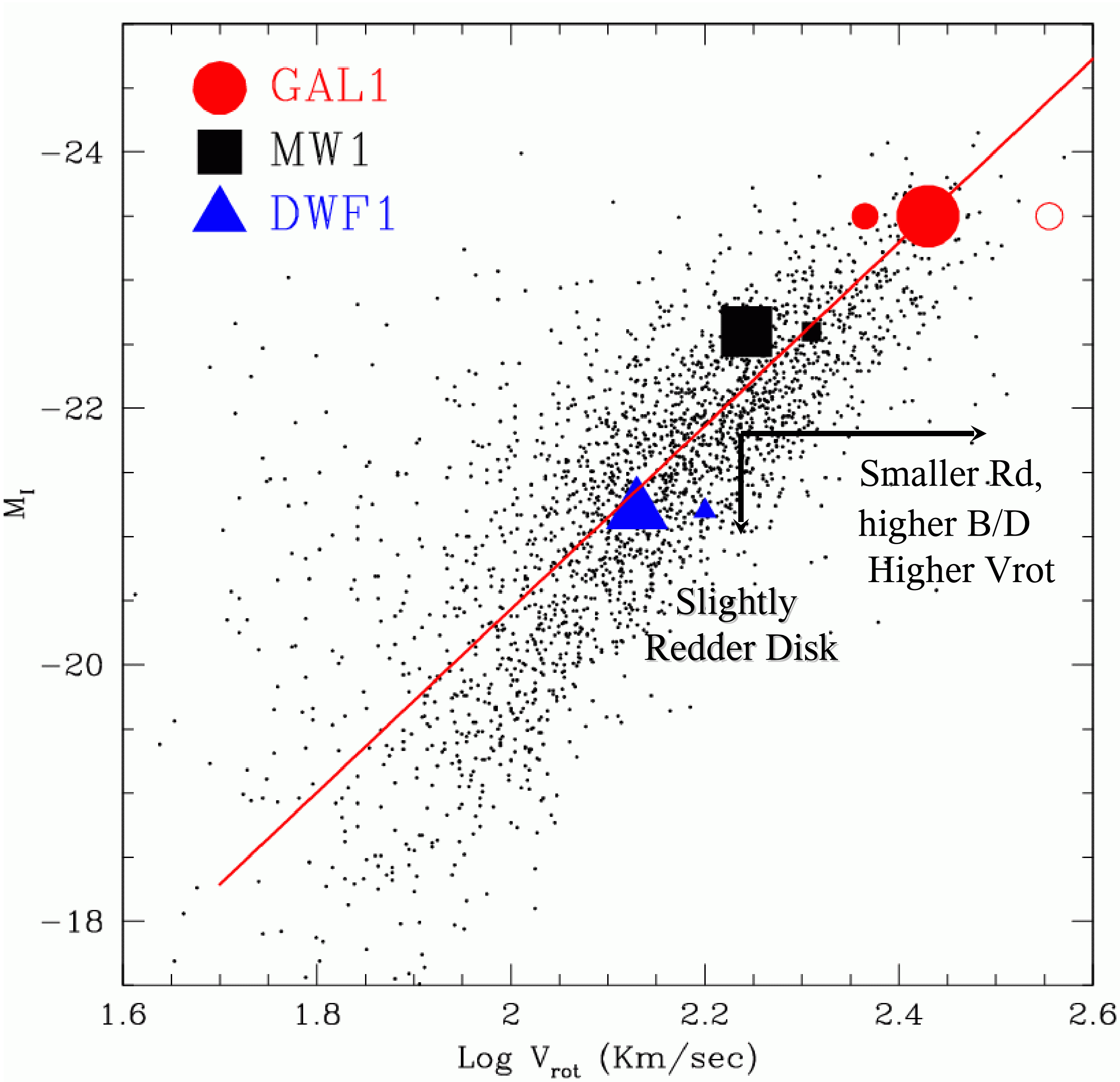
....there are issues at small scales (< 1 million light years)

Issue (1) Abundance of satellite galaxies of the Milky Way



Simon & Geha 2007

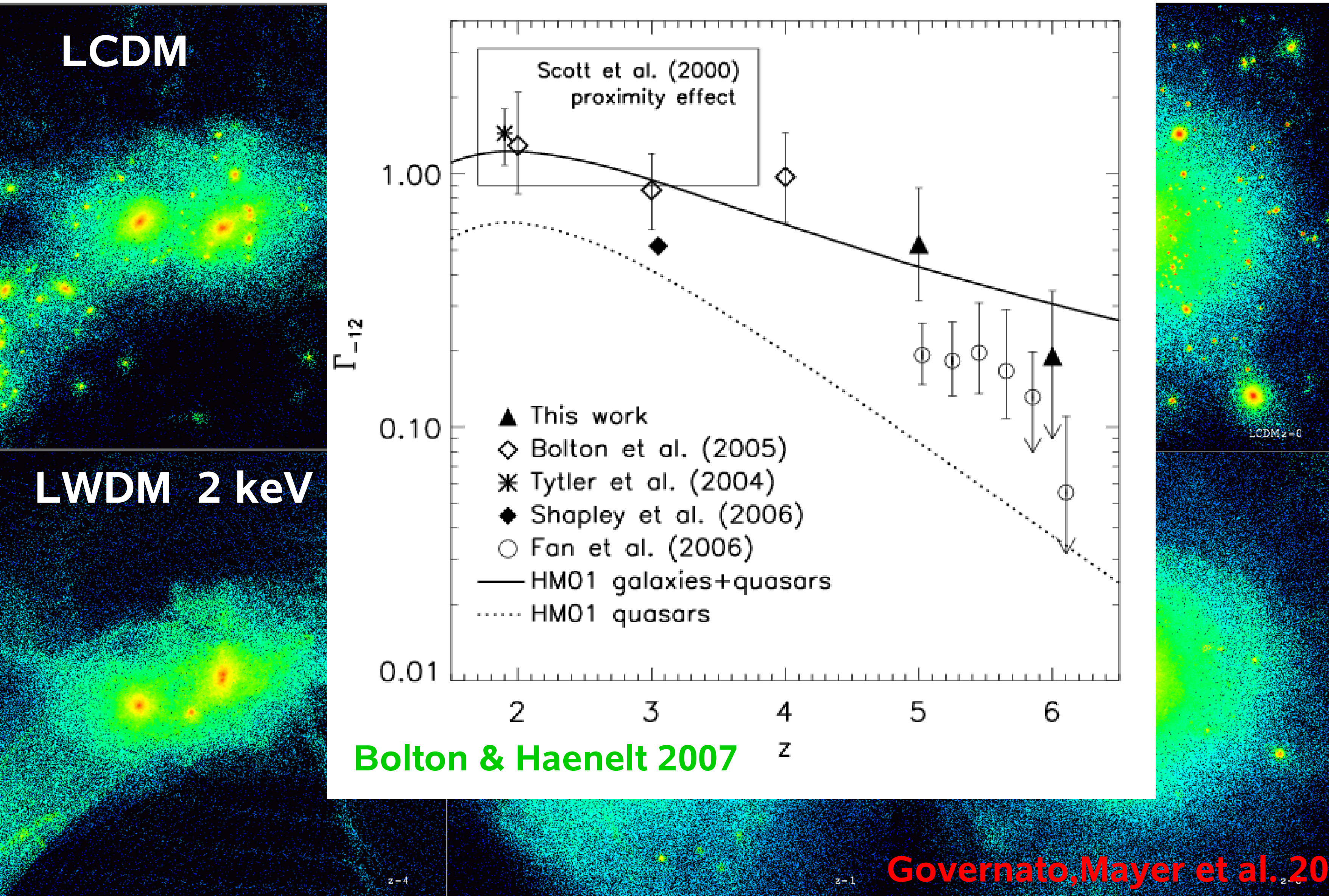
$V_{circ} = (GM/R)^{1/2}$


GAL1
MW1
DWF1
Smaller Rd,
higher B/D
Higher Vrot
Slightly
Redder Disk
−24
−22
−20
−18
1.6
1.8
2
2.2
2.4
2.6
M_I
Log V_{rot} (Km/sec)

A drastic solution: change power spectrum/cosmology

Example: warm dark matter (WDM) --> free streaming due to non-zero thermal velocity reduces power at small scales

…but data on reionization better matched by CDM ---> structure formation delayed in WDM, not enough galaxies for reionization

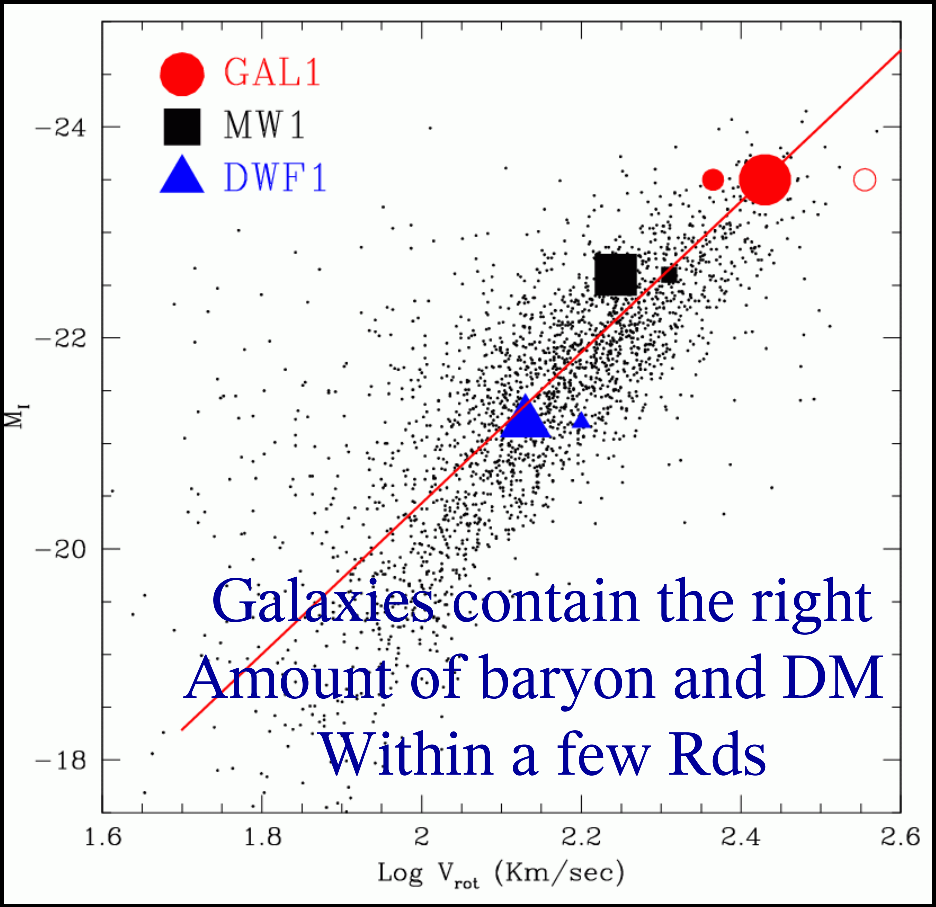


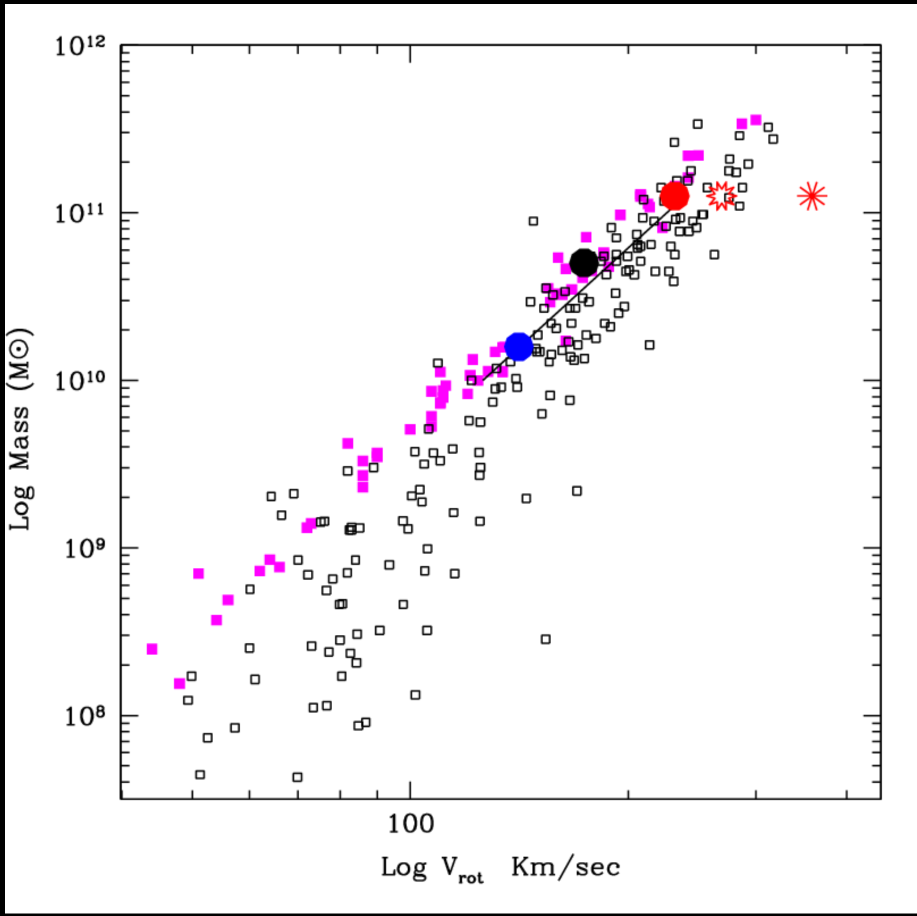
Bolton & Haenelt 2007

Governato, Mayer et al. 2004

I band TF & baryonic TF

Governato et al 07





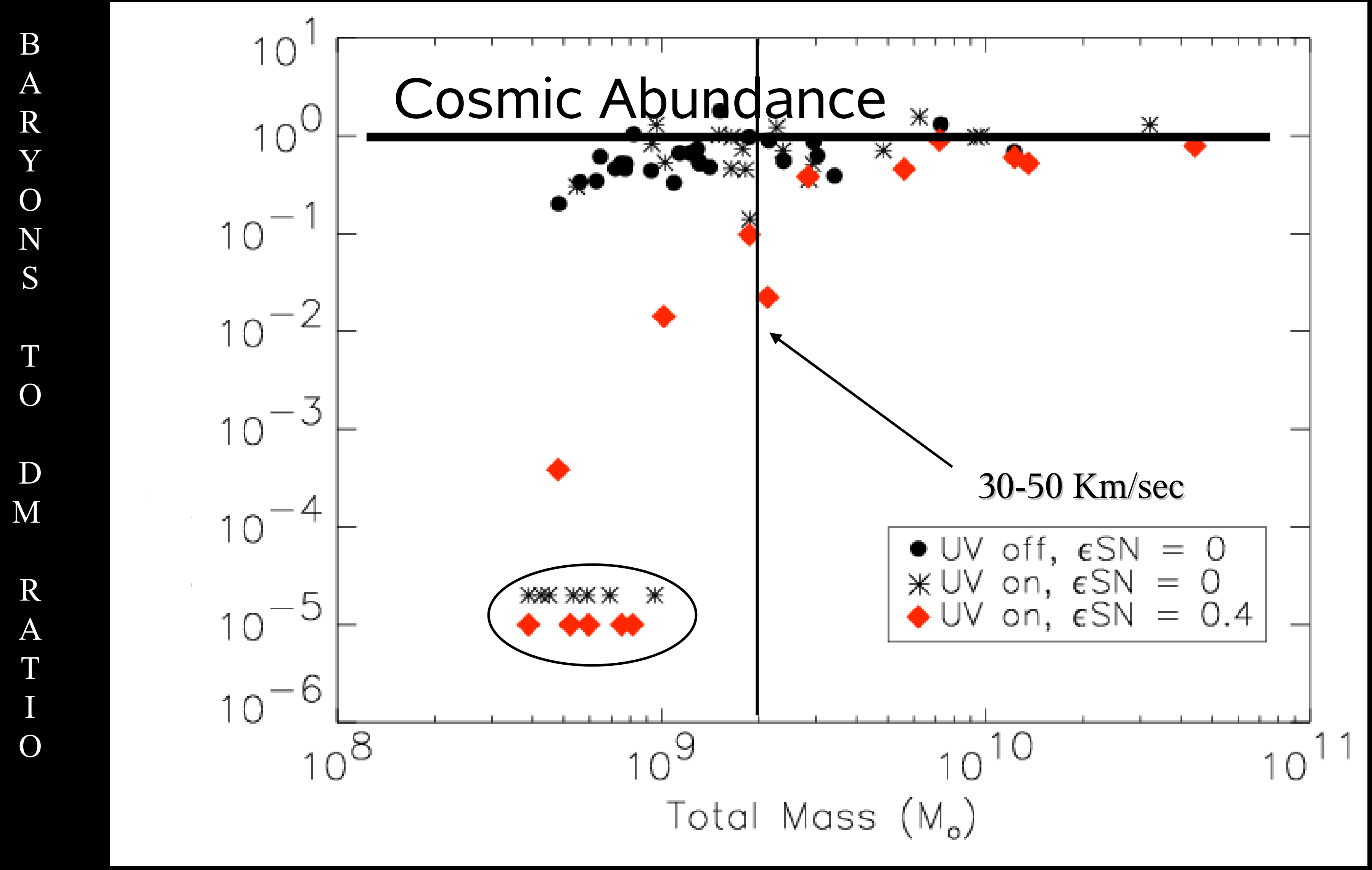
Giovanelli & Haynes 05

Rd fitted to I band stellar profile. Vrot measured from cold gas at 2.2-3.5Rd

MacGaugh et al 2005

Includes stars+cold gas

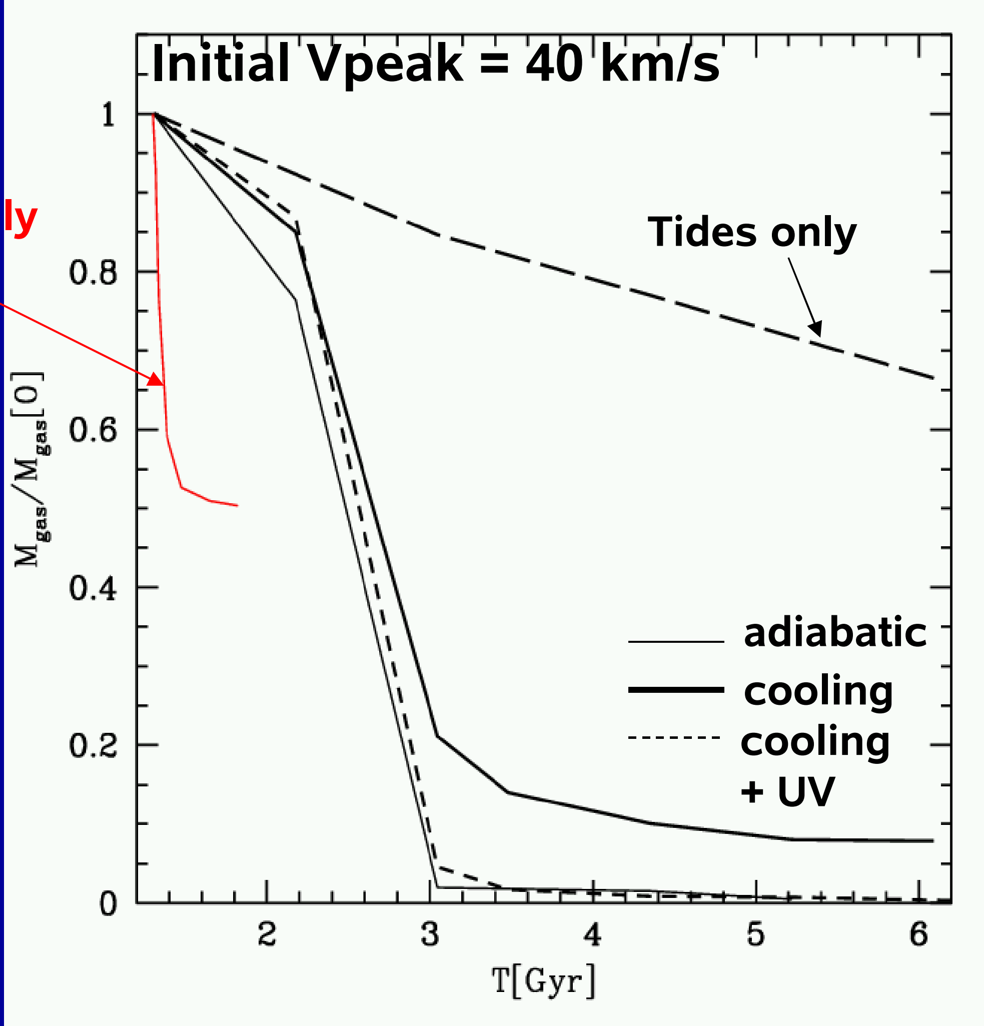
MW Satellites: UV field + SN feedback on



Gas mass loss: tides + ram pressure

- Ram pressure produces higher mass loss relative to tides.
- Stripping with tides + ram pressure higher relative to ram pressure only since potential well of the dwarf is substantially weakened (Vpeak drops)
- With cosmic UV bg (z > 1) gas is lost, star formation truncated

Ram pressure only



ORBIT:
Apo=150 kpc
Peri=30 kpc

"standard" cosmic UV bg (Haardt & Madau 1999)

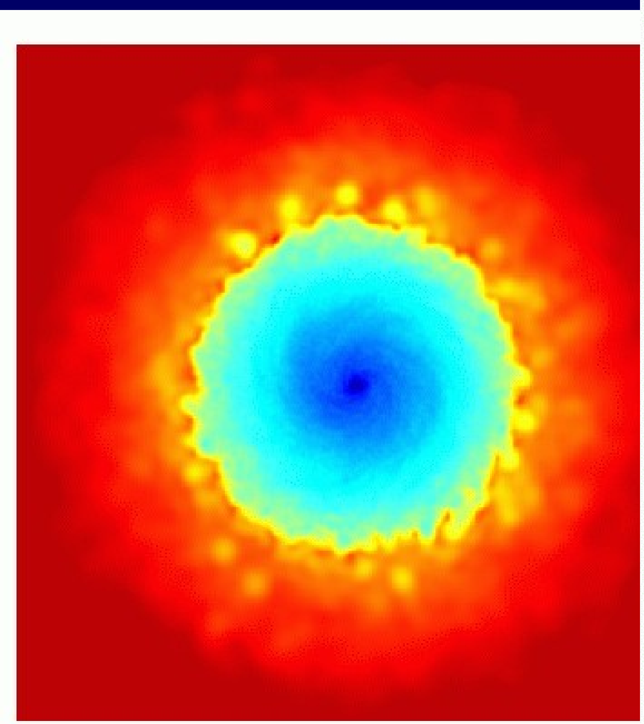
Mayer et al. 2006

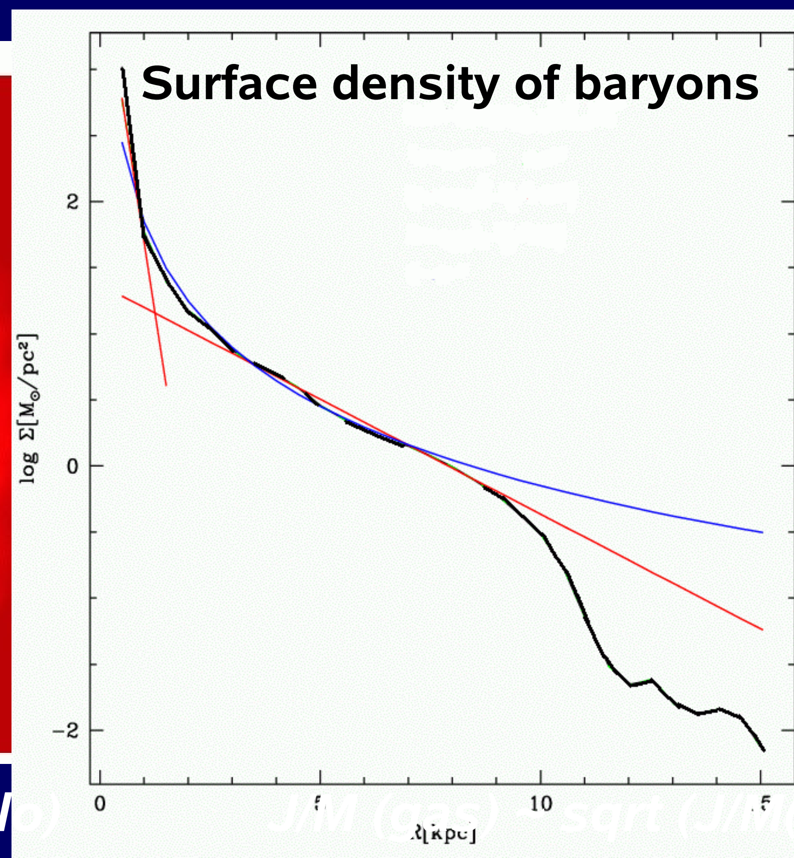
3D simulations confirm: no exponential profiles

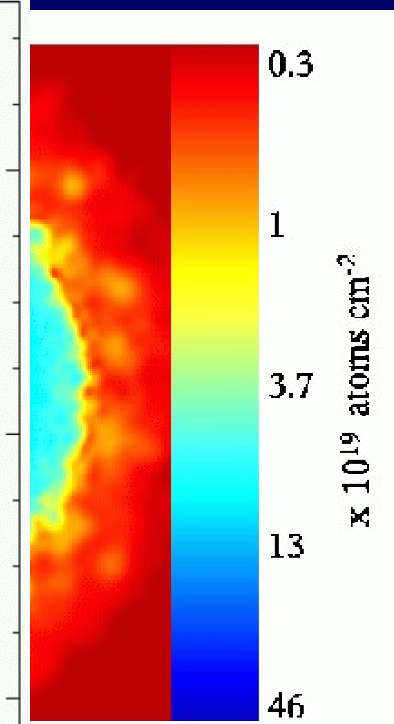
Does this mean assumption that J/M of accreting gas ~ J/M of dark matter not correct ?

Not clear yet – gas in simulations can lose angular momentum by artificial viscosity and fall to the center + spiral arms transport angular momentum (spiral pattern can be amplified by noise in simulations)

Key input of future observations: measure angular momentum of gas accreting onto galaxies (gas already in disk affected by internal dynamics – e.g. spiral arms)





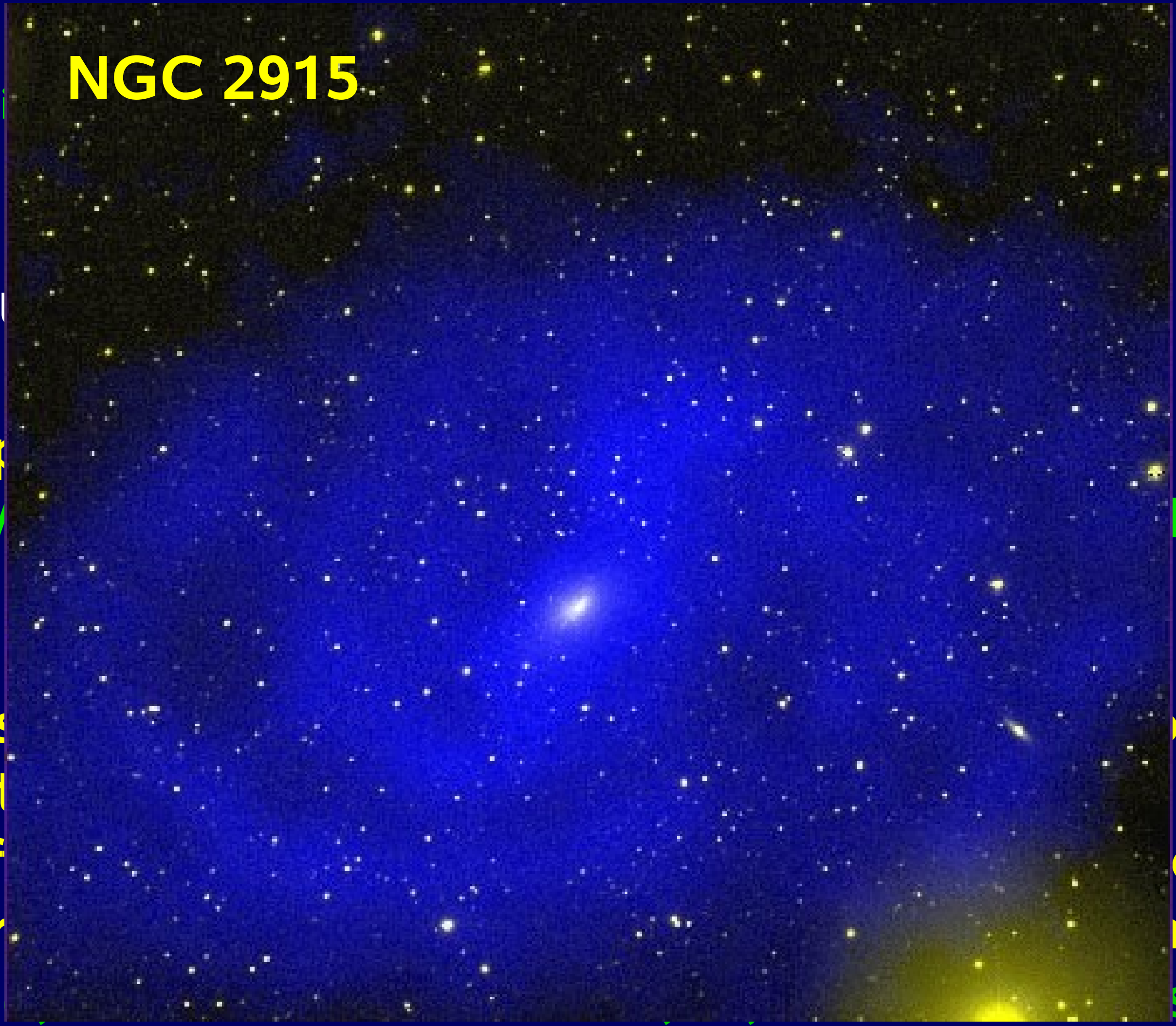


J/M (gas) ~ J/M (halo)

J/M (gas) ~ sqrt (J/M(halo))

What if the progenitor of some dSphs was gas dominated?

Mayer, Kazantzi



Plausible assu

(3)Most late-typ > 0.5 today (e.g. M loore 2004)

(2)Both hydro s rmation naturally obt star formation ef ed star formation or ation (Schaye 200 ssen 2005; Robertson et al., in prep.)

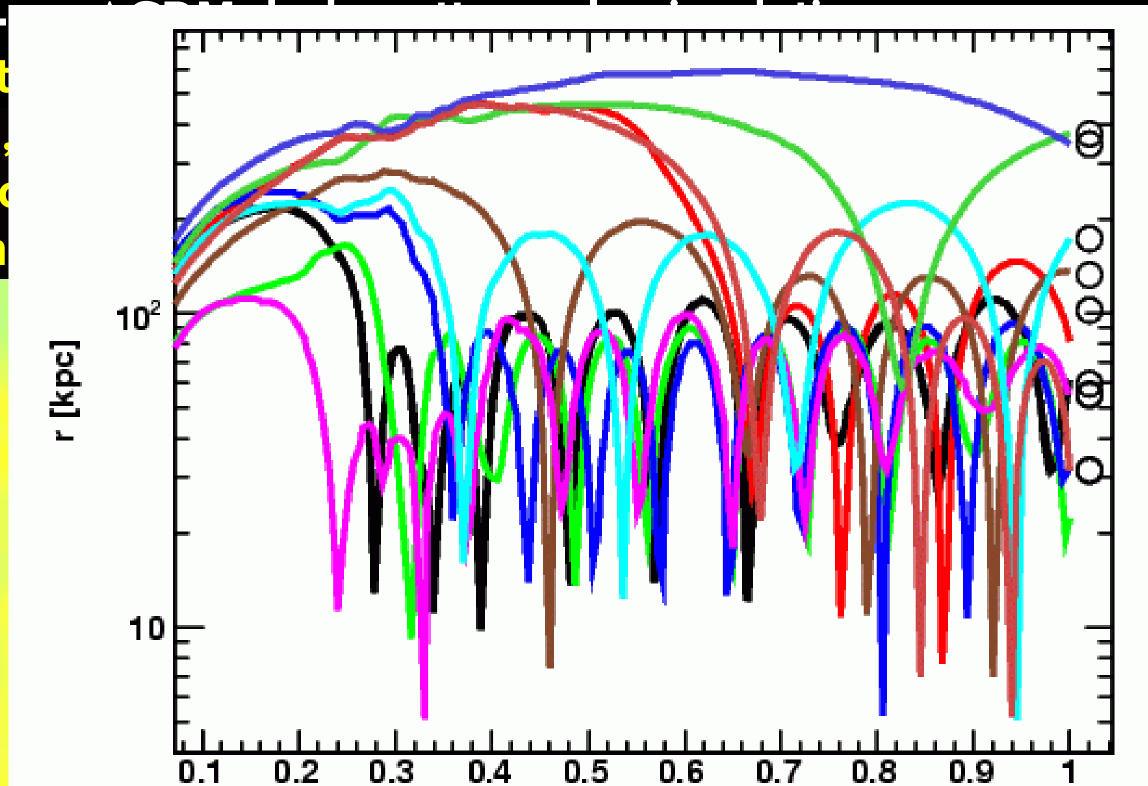
-Pick satellites with Vmax ~20-25 km/s today (consistent with kinematics of darkest dSphs, Draco and Umin) and within 100 kpc from MW in hi-

-Trace the orbit ... t

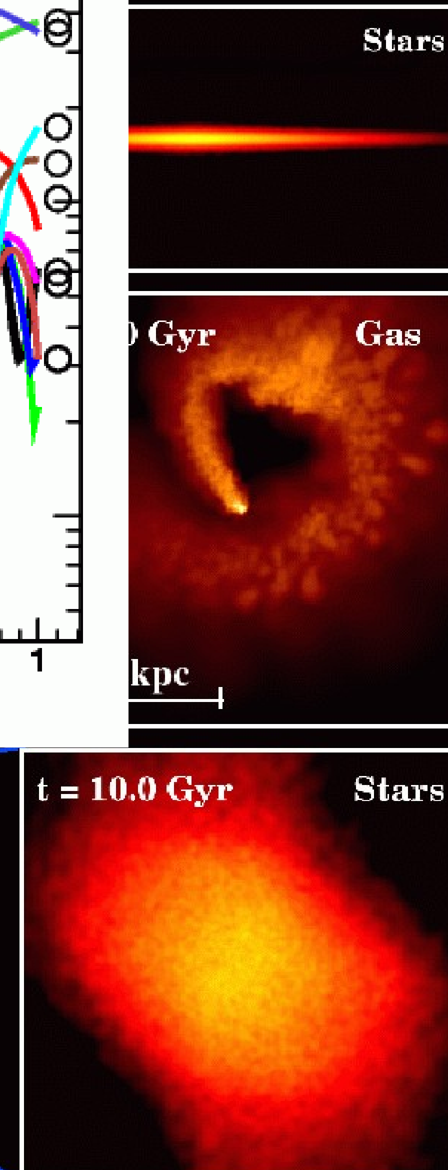
fell in at z > 1.5,

-Make hi-res mo

in disk and sim



Diemand et al. 2007

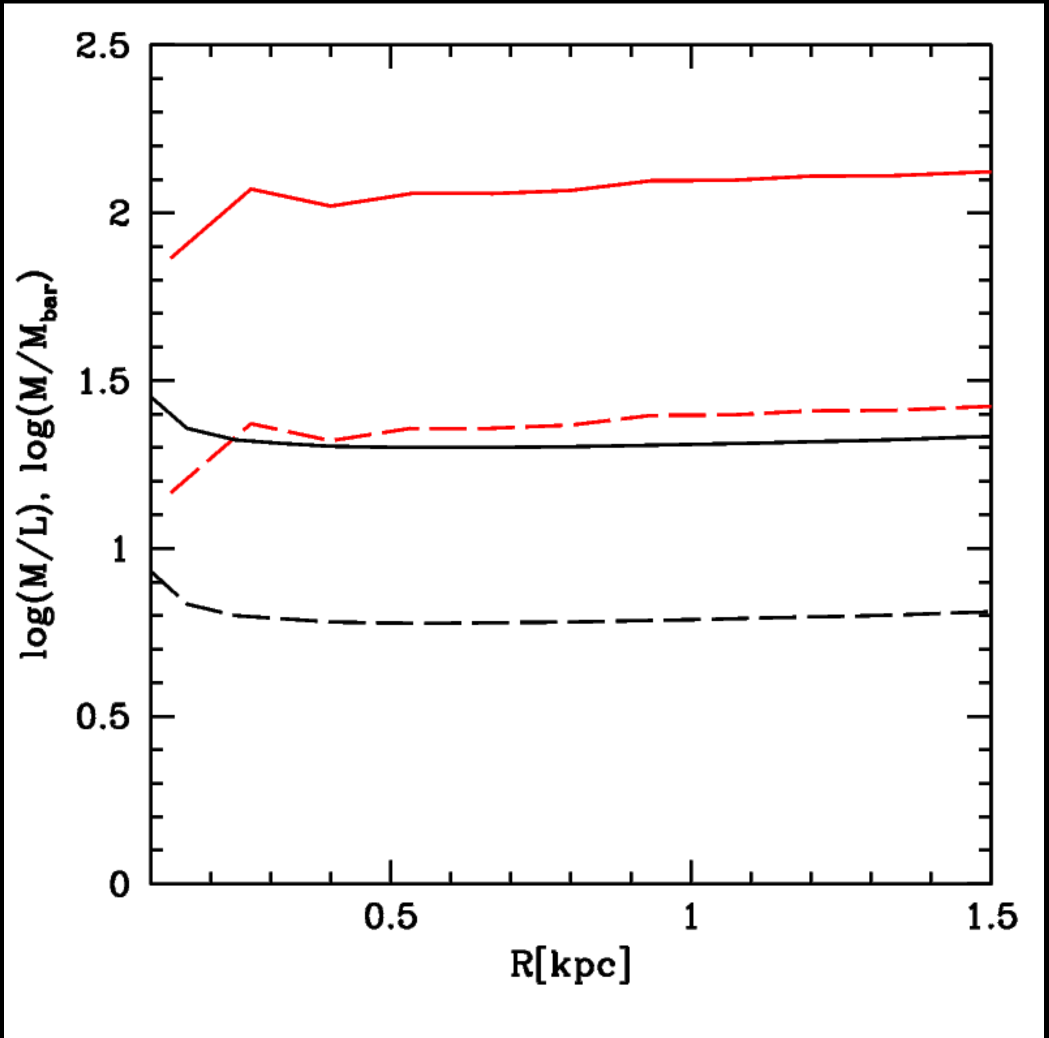


Star formation suppressed because gas density always too low (gas warm and ionized by UV bg as Vmax drops to < 30 km/s due to tidal shocks)

Dark matter and stars are only partially stripped (suffer only tidal effects) and are stripped at similar rate ---->

Mdm/Mstars ~ constant = final Mdm/Mbaryon > 100!

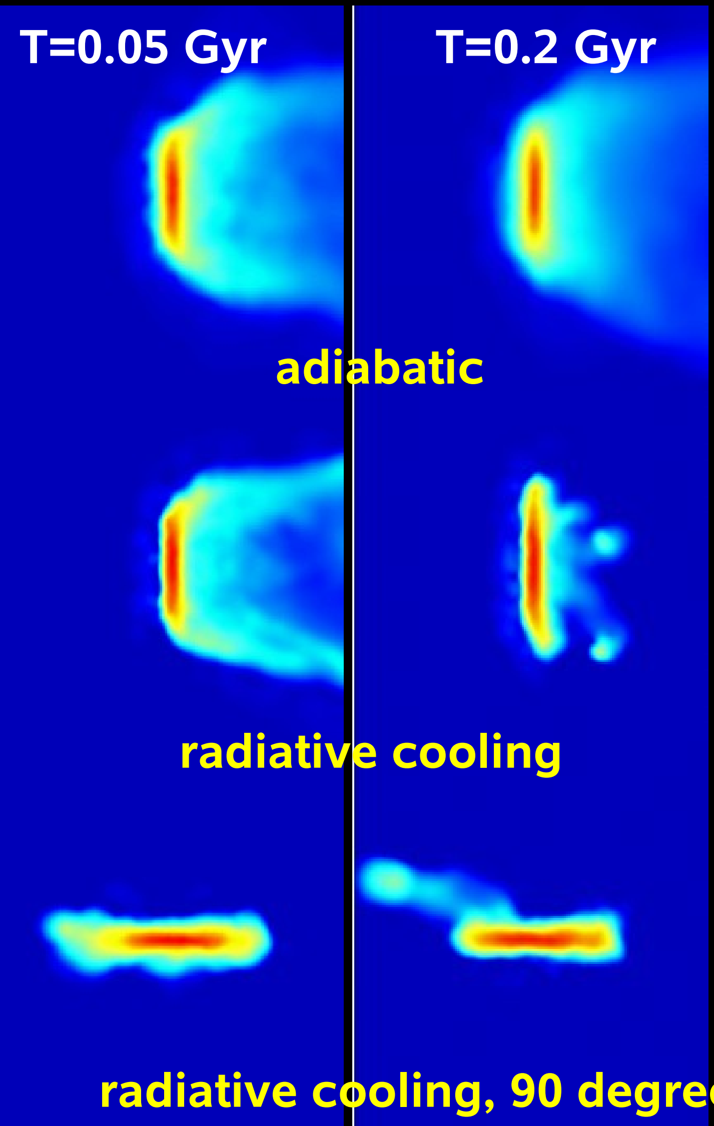
Naturally obtain very large mass-to-light ratio starting from a normal mass-to-light ratio (~ 10)



Tube Flow runs: ram pressure only

2 million SPH particles to control numerical artifacts

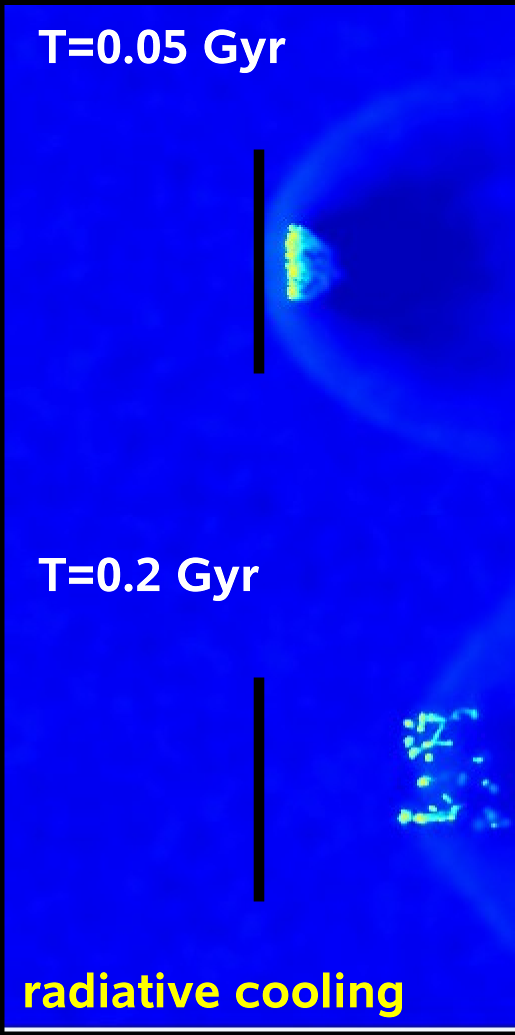
Vpeak=40 km/s



-- Complete stripping requires Vpeak < 30 Km/s (also Marcolini, Brighenti & Matthews 2003 with eulerian code)

-- Stripping reduced with cooling, less gas leaves the disk + fall back of some gas that leaves the disk

Vpeak=25 km/s



Angular momentum – II
The exponential profile problem

Let's drop the assumption that disks are exponential; can we *obtain* an exponential disk self-consistently?

- keep the other two assumptions, (1)J/M(gas) = J/M(dm) and (2)conservation of angular momentum of gas during collapse
- use the distribution of J/M(r) of dark matter halos from cosmological simulations --→ *$J \sim r^{-\alpha}$, $\alpha \sim 1.1$* (Bullock et al. 2001):

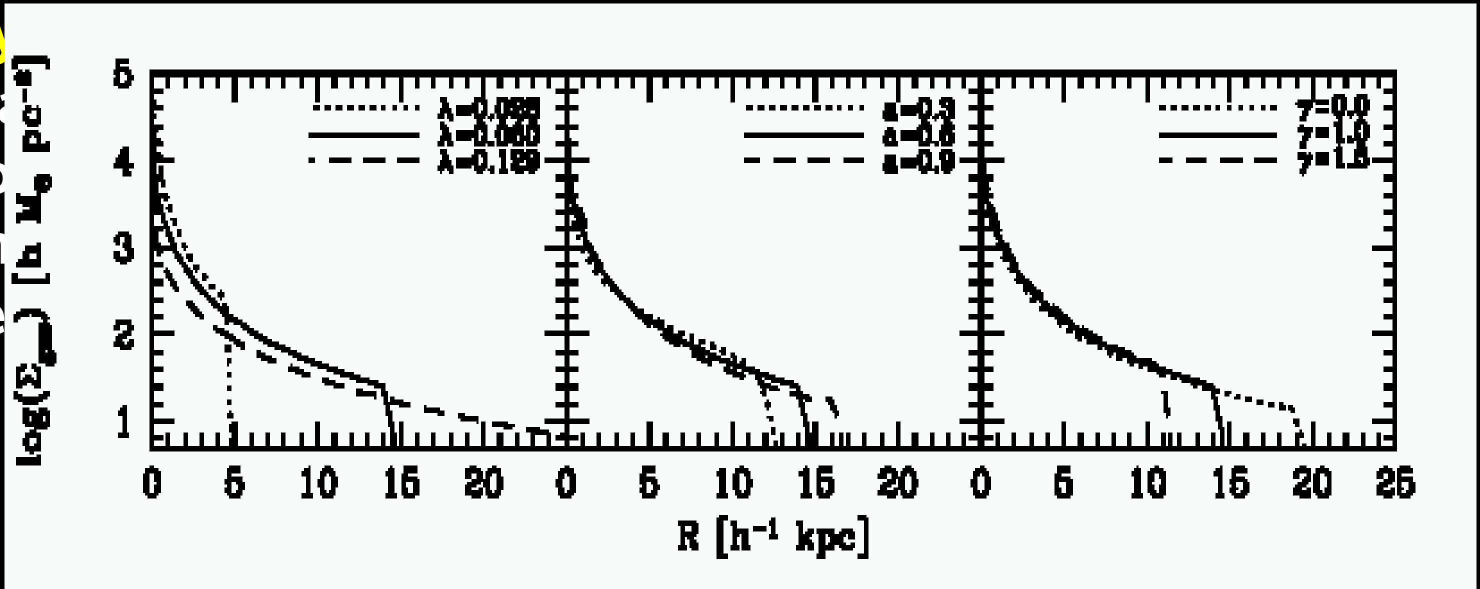
PROBLEM (y

1- D spheric

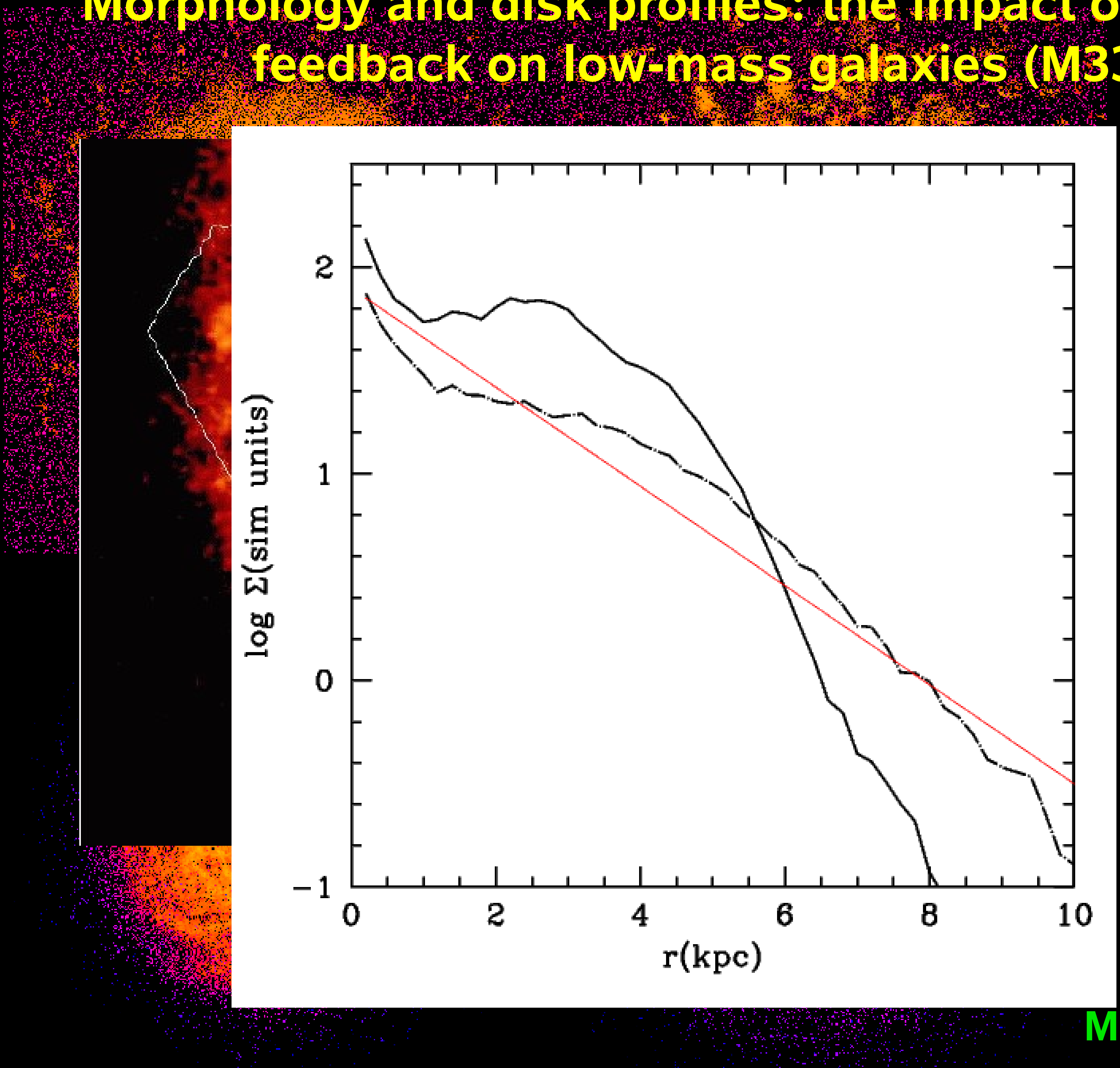
et al. 2007) o

of angular m

than expone



Morphology and disk profiles: the impact of blast-wave feedback on low-mass galaxies (M33-size)



Mayer et al. 2008

Why do we care about LG dwarf satellites?

- They are the closest and thus best studied among dwarf galaxies ----> galaxy formation

- They are the most dark matter dominated galaxies known -→ nature of dark matter

- They are associated with the CDM crisis at small scales, namely the missing satellite problem -→ structure formation

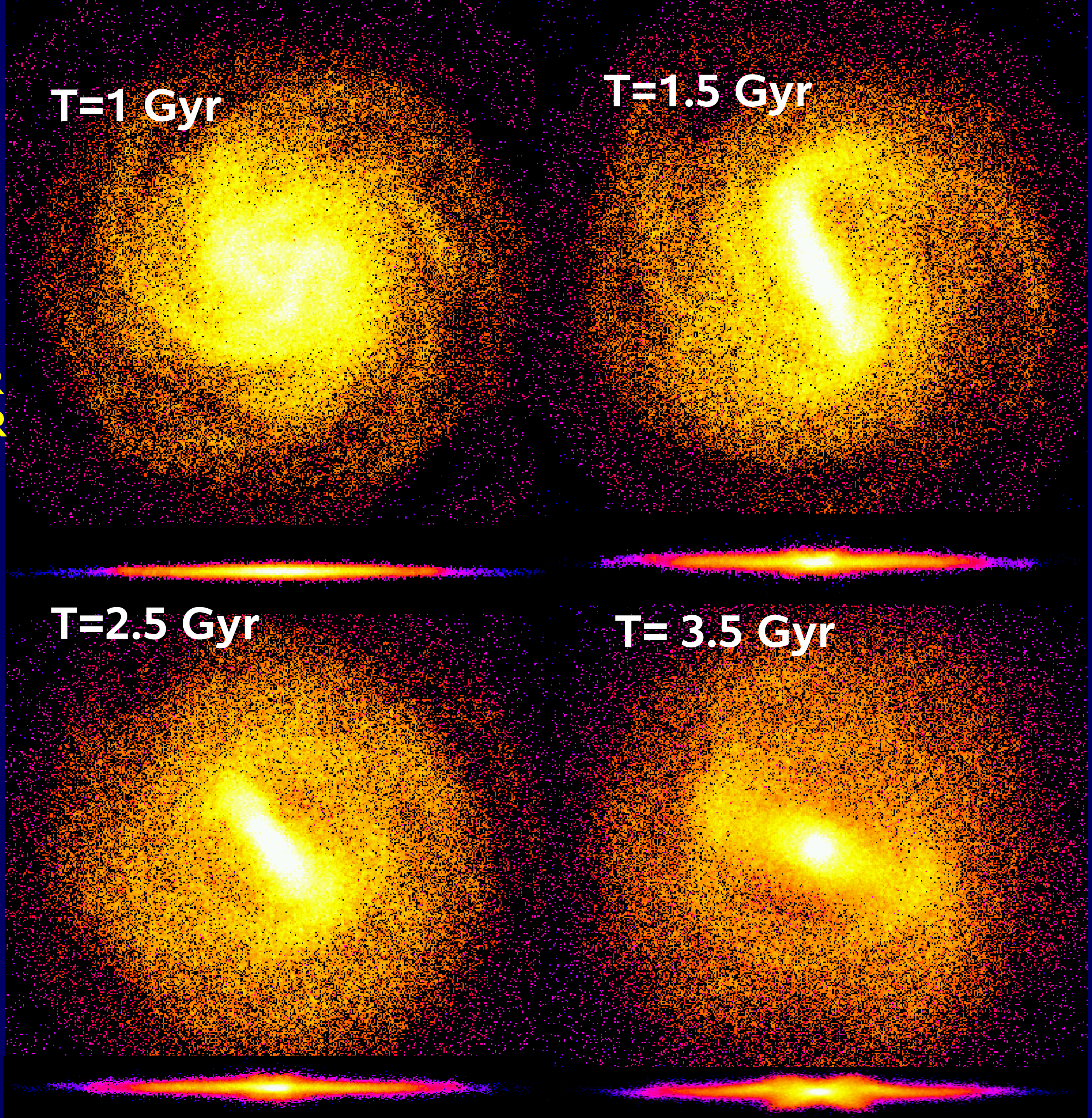
1.5-3 million particles/models, 50 pc force resolution

COLLISIONLESS SIMULATIONS (i.e. ONLY STELLAR AND DARK MATTER COMPONENT)

(log) stellar density shown

MW-sized model in a CDM halo, Isolated galaxy (no perturbers)

Debattista, Mayer et al. 2006.

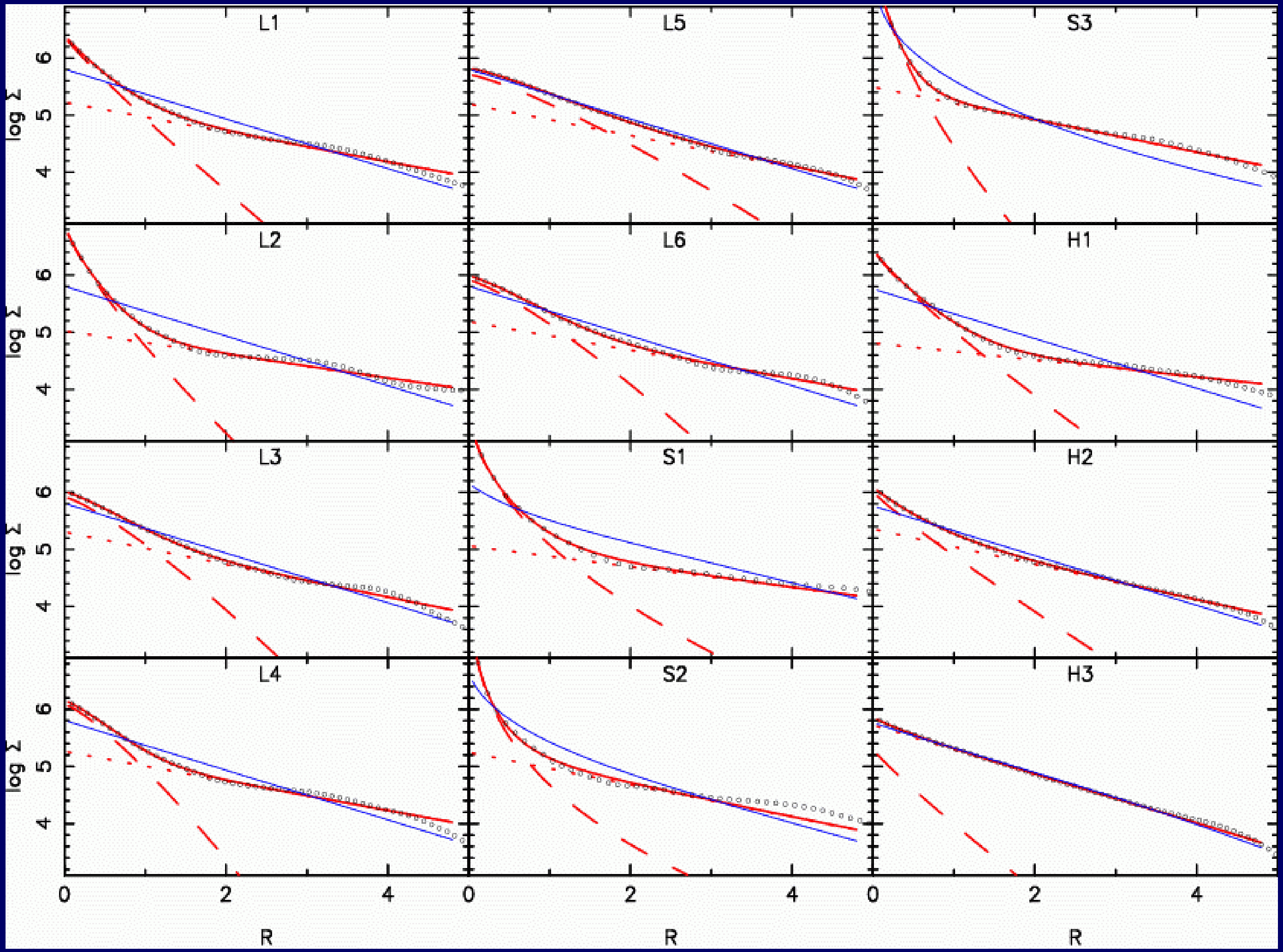


---*and non-exponential profiles…*

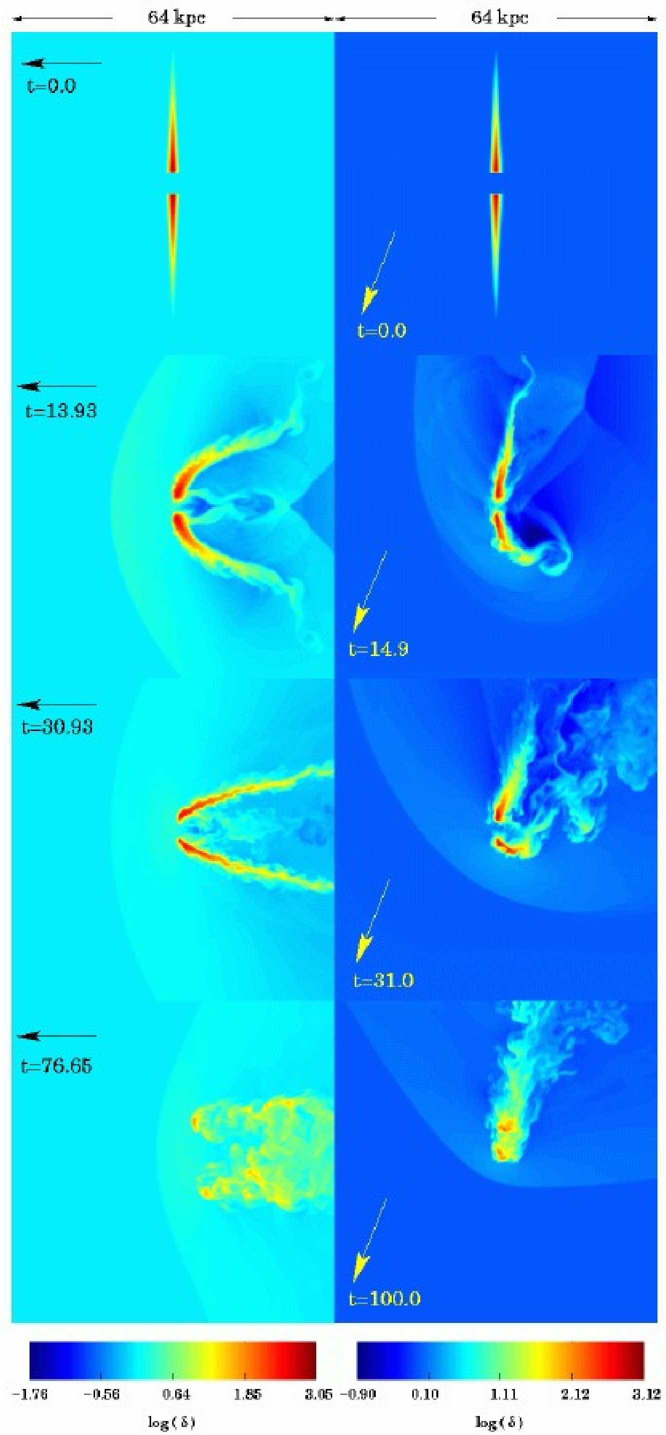
Bar formation shapes the evolution of stellar density profiles

Steepening in the center and flattening in the outer disk in bar unstable models (already in Hohl 1971)

Disk scale length (outside bar) grows by up to a factor of 2

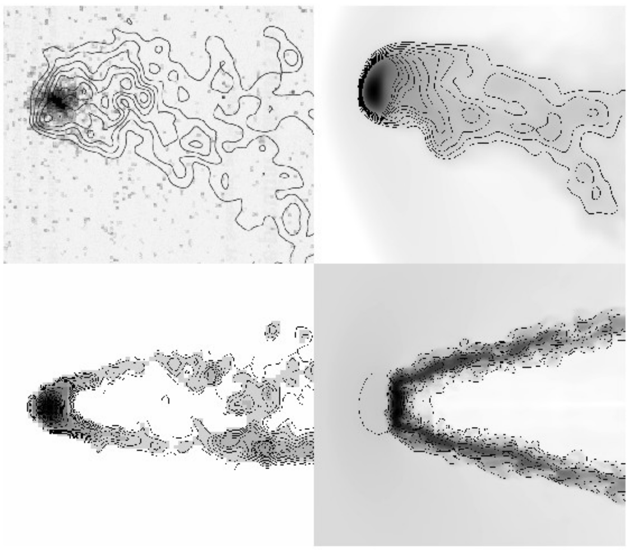


Debattista, Mayer et al. 2006



(Quilis et al. 2000)

Result: truncation of star formation, passive spiral or S0 (but tides crucial to shape morphology – see next talk by Oleg Gnedin)



Tests with isolated galaxy N-Body+SPH models
(Stinson et al. 2005)
SF efficiency 0.05/Tdyn
SN efficiency = $0.6 * 10^{51}$ erg

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

Why should we care about the Local Group?

- It is the best known sample of galaxies in the Universe, hence the most important testbed for theories of galaxy formation

- We need to understand the origin and history of present-day galaxies if we want to understand the high redshift Universe. The history of LG galaxies can tell us a lot about history of mass, light and chemistry in the Universe

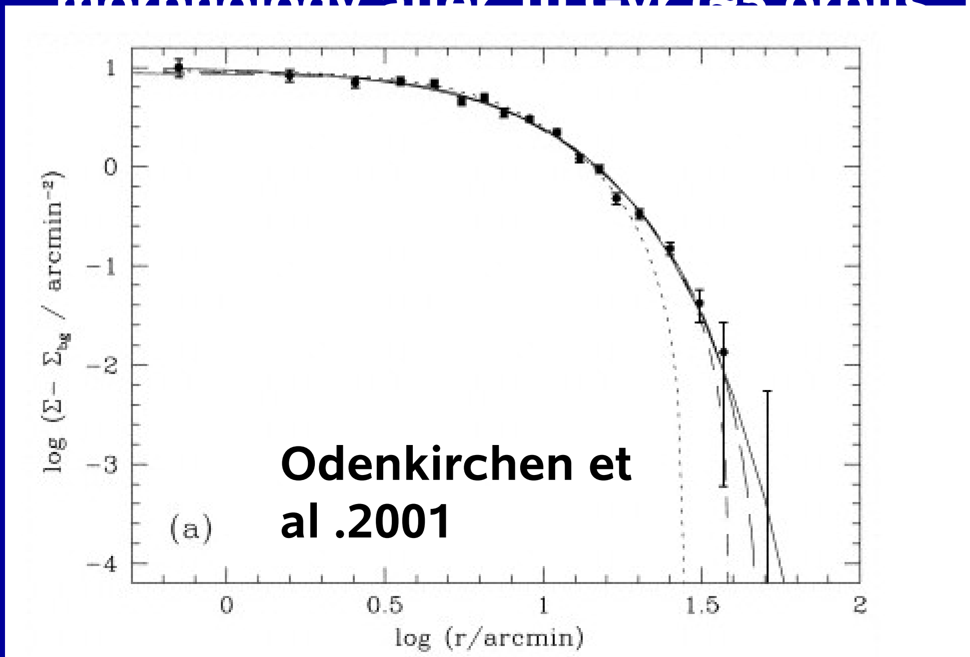
EVEN DWARFS WITH MASSIVE HALOS TRANSMUTE

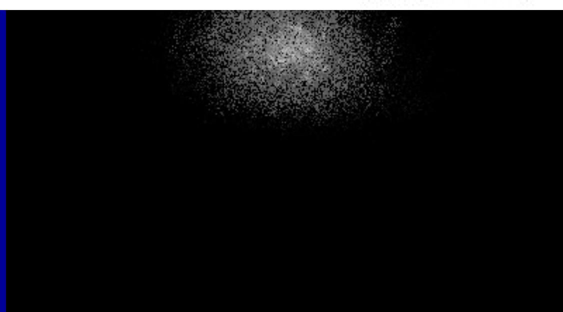
Initial Vpeak=35 km/s, fdisk=4% c=16 NFW HALO, shown is morphology after 10 Gyr (~5 orbits, Rperi=25 kpc, Rapo=120 kpc).

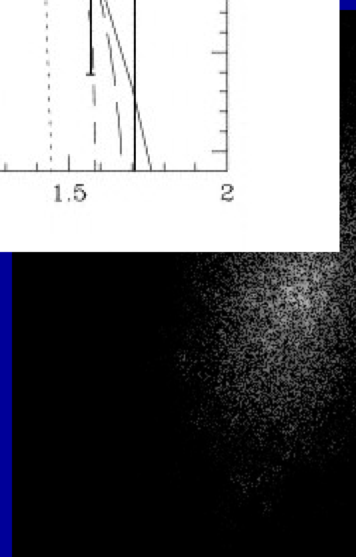
).

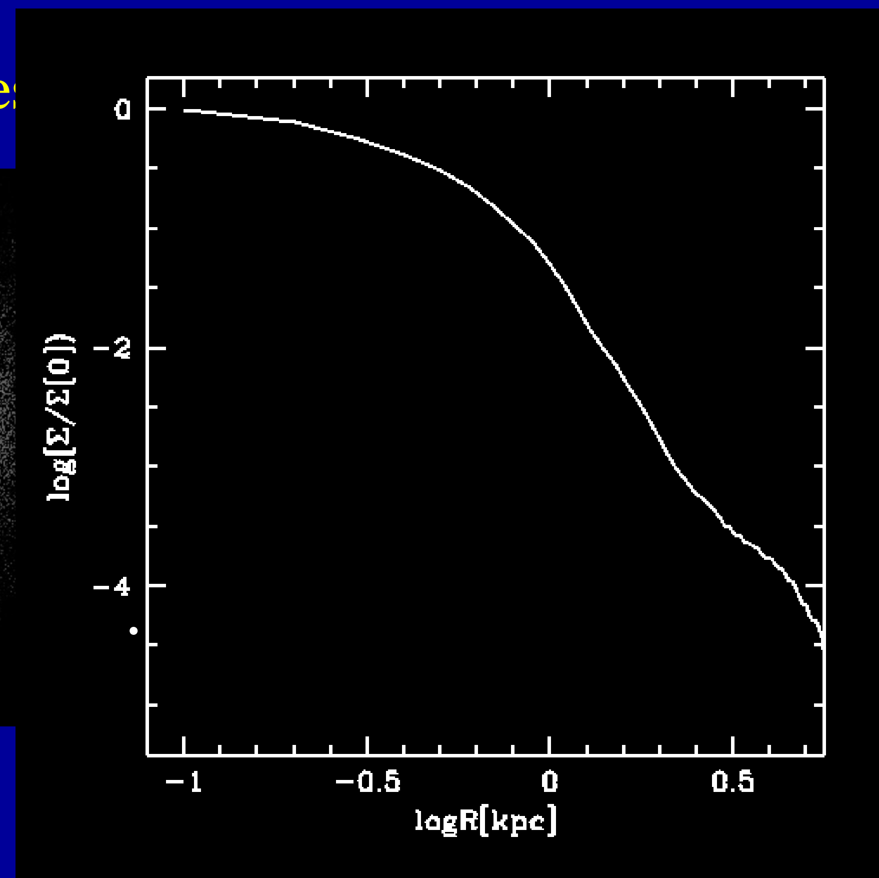
d but heating and instabilities

Read et al. 2006; Gnedin et al. 1999)

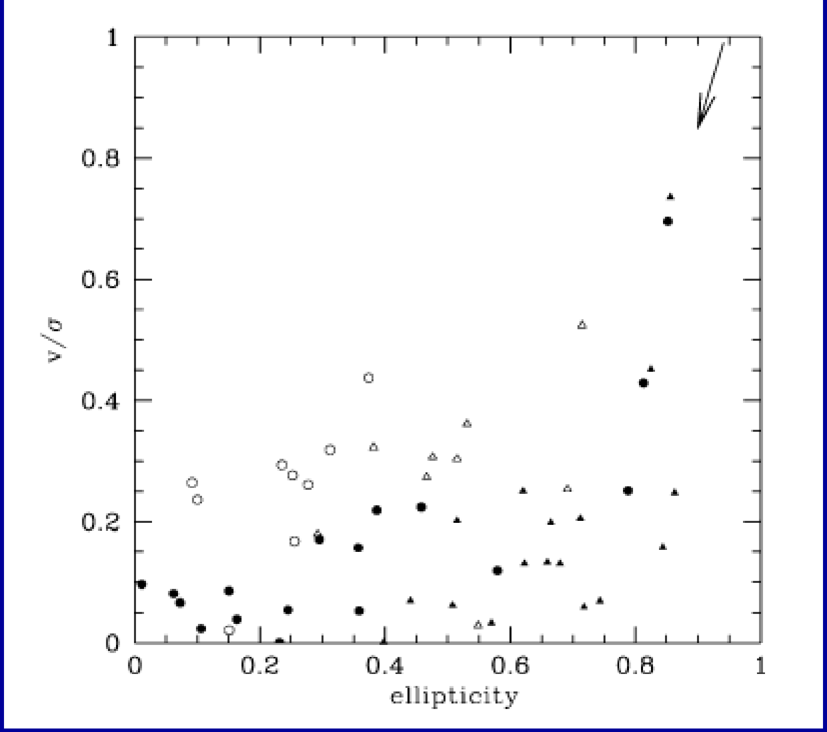








V/σ after 8 Gyr



Suite of different initial models
and different orbits

Within R=Re

Mayer et al. 2001a

Remnants are moderately triaxial

Different symbols refer to line of sights along different axes

Filled Symbols=LSB disks, > 23 mag $arcsec^{-2}$

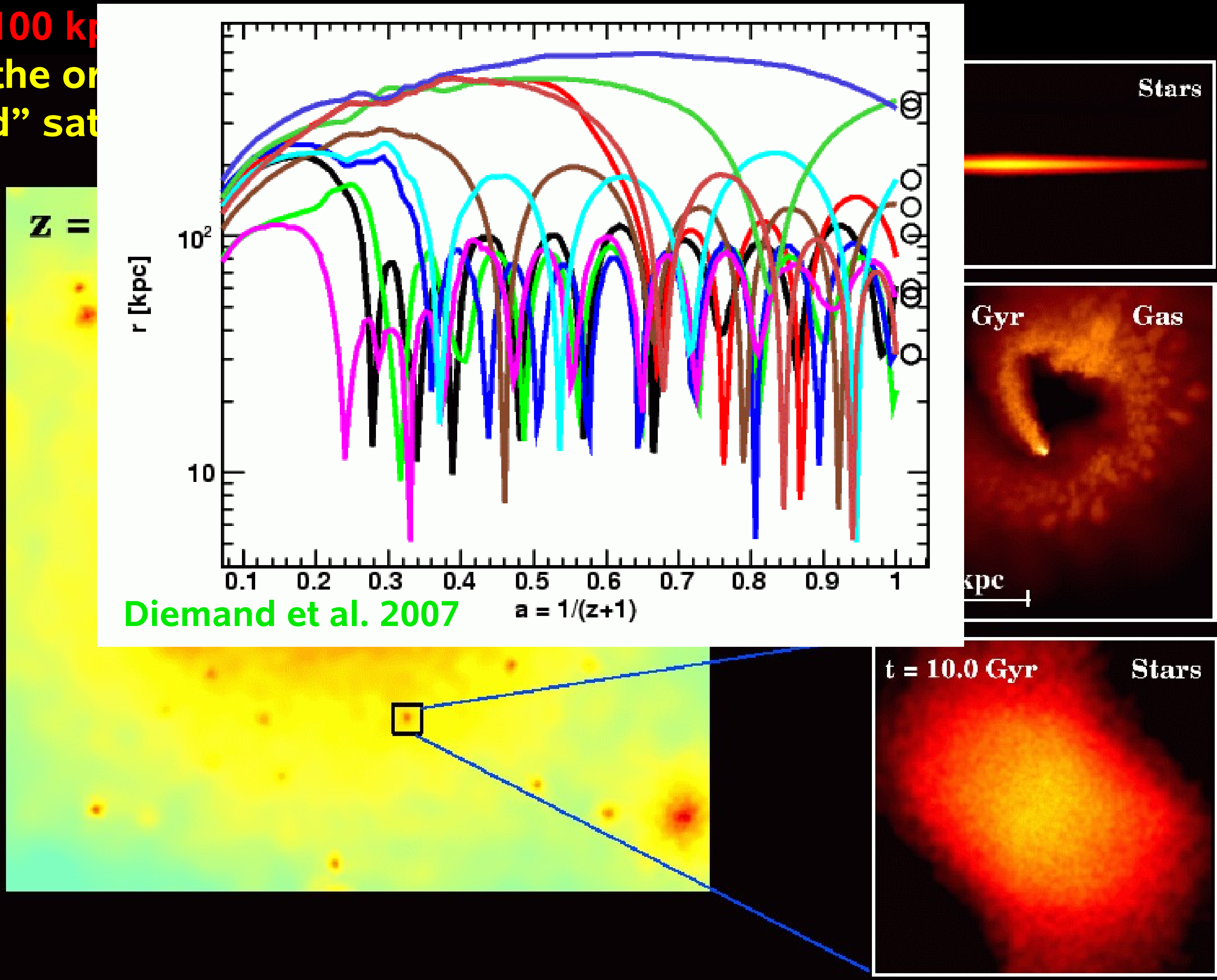
Open Symbols=HSB disks, < 23 mag $arcsec^{-2}$

Loss of angular momentum due to bar instability (vt ↓) +
heating by tides/buckling (σ ↑)

Tidal stirring produces pressure supported remnants as dSphs

-Pick satellites with Vmax ~20-25 km/s today (consistent with kinematics of darkest dSphs, Draco and Umin) and within 100 k

-Trace the or
are “old” sat

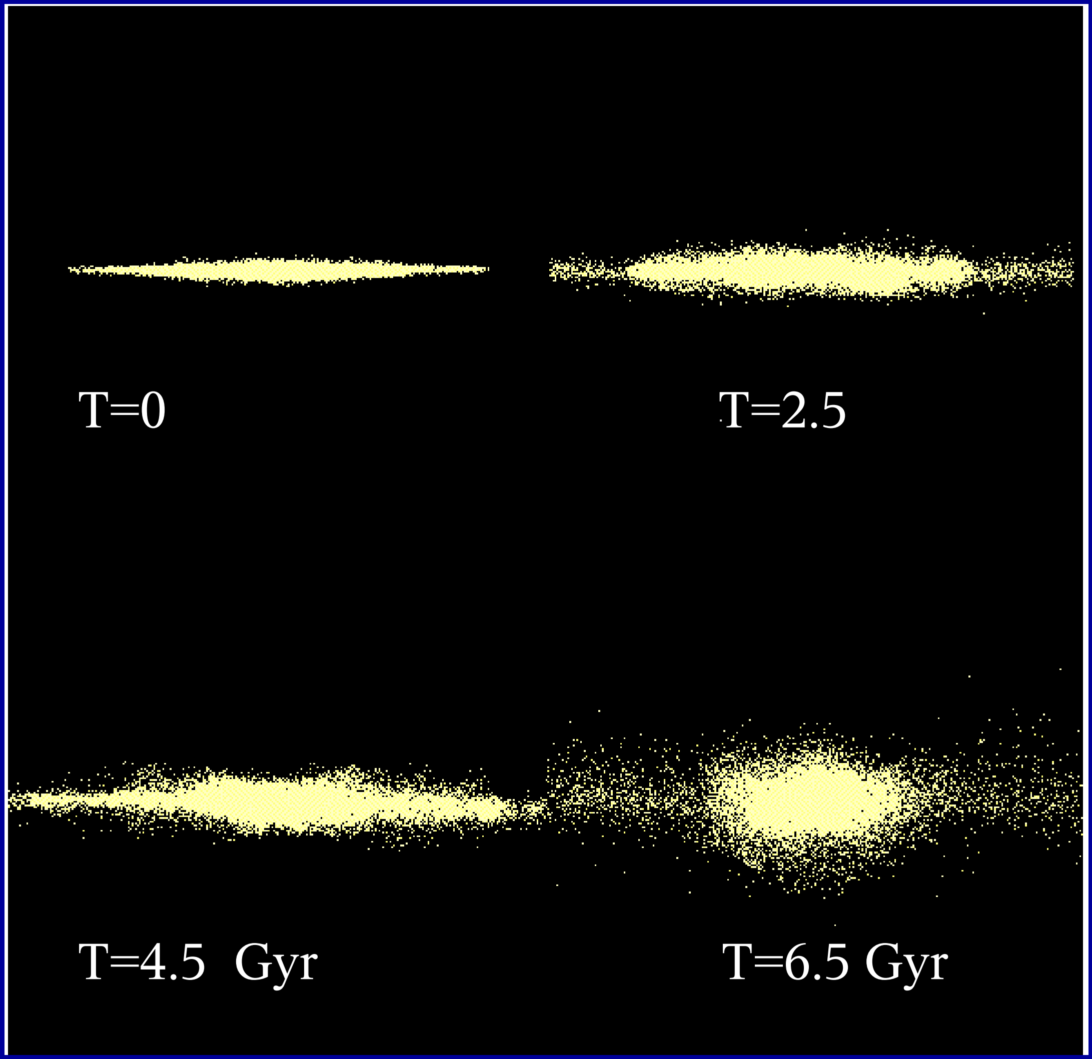


Diemand et al. 2007

Tides induce bar/buckling instabilities
Turn disk into spheroidal

LSB disk
apo/peri = 5
Apo=250 kpc
Peri=50 kpc

Star particles shown →



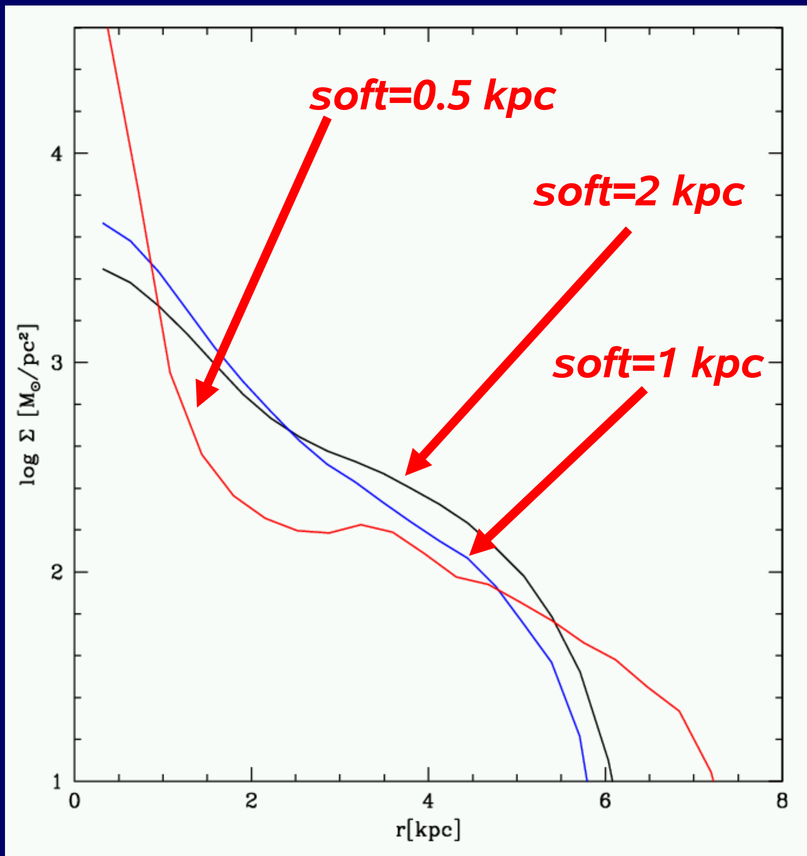
10 x 10 kpc

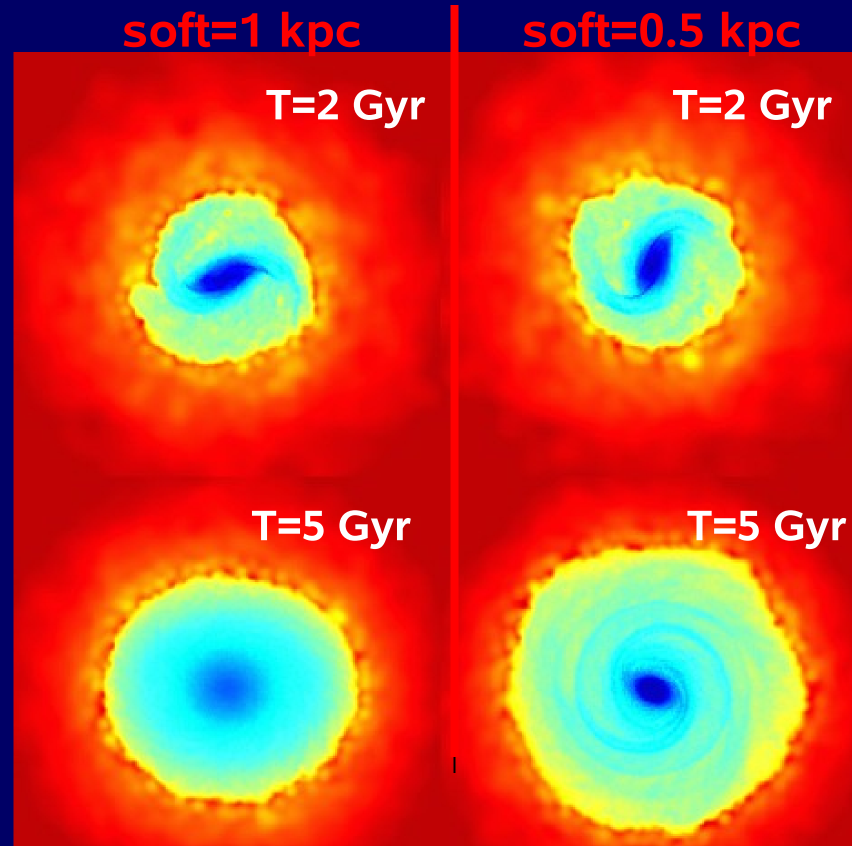
Mayer et al. 2001a,b
Mayer et al. 2002

See also
Raha et al. (1991)
Merritt & Sellwood (1994), Combes et al. (1990)

OUTLINE?

Result confirmed by hydro simulations.





Softening and resolution affect disk dynamics and thus the final disk mass distribution

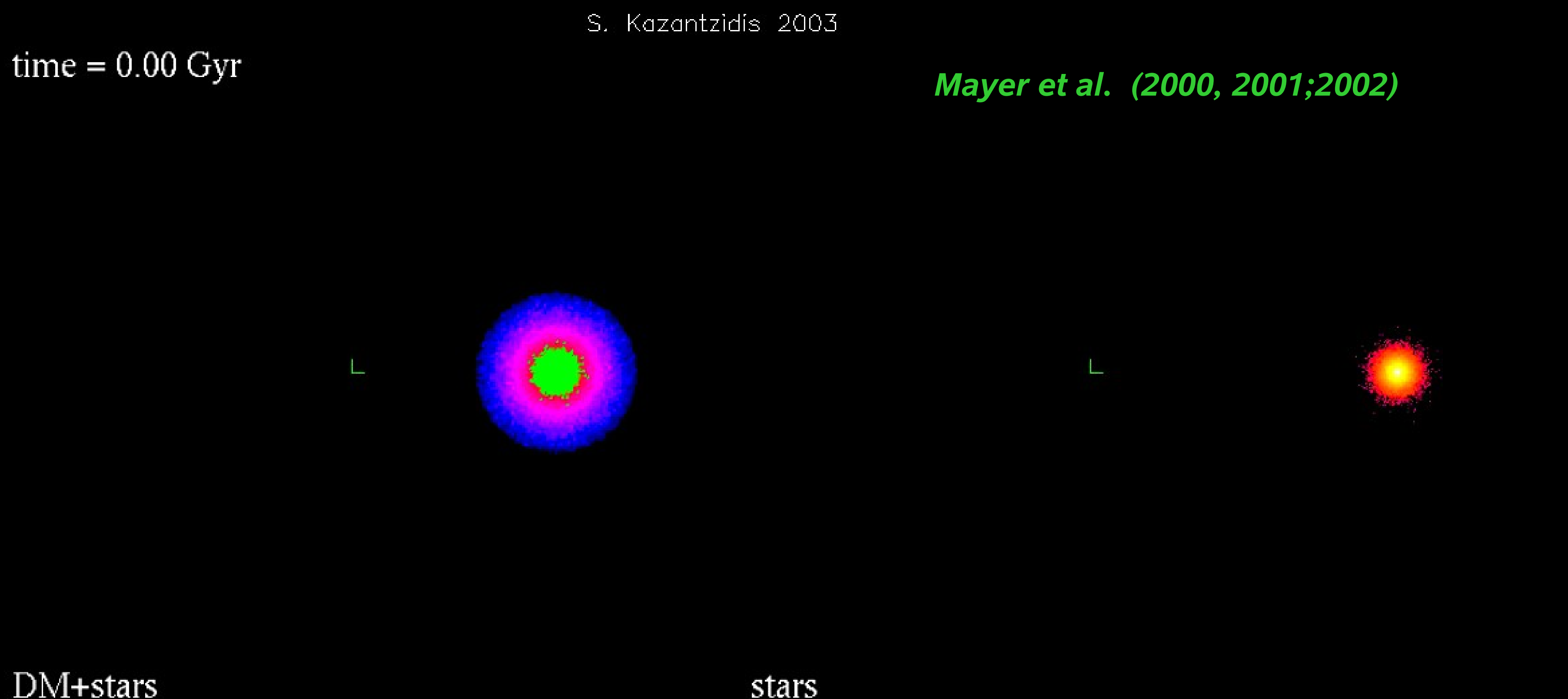
The presence of a bar increases the scale-length of the outer (nearly exponential) disk by a factor of 2

Important because the majority of disk galaxies is barred!

TIDAL STIRRING of dwarf galaxy satellites

Not enough resolution in subhalos of cosmological simulations with hydro ---->
study interaction between a dwarf galaxy and a massive spiral with hi-res N-Body + SPH sims (with GASOLINE), a few million particles per single dwarf model.

Initial conditions
(1) orbits and structure of galaxies/halos (NFW) from cosmological runs + scaling relations between baryonic disk and halo from Mo, Mao & White (1998)
(2) free parameters (e.g. disk mass fraction, gas fraction in disk) chosen based on observations of late-type dwarfs (e.g. de Blok & McGaugh 1997; Geha et al. 2006)



Mayer et al. (2000, 2001;2002)

Key questions

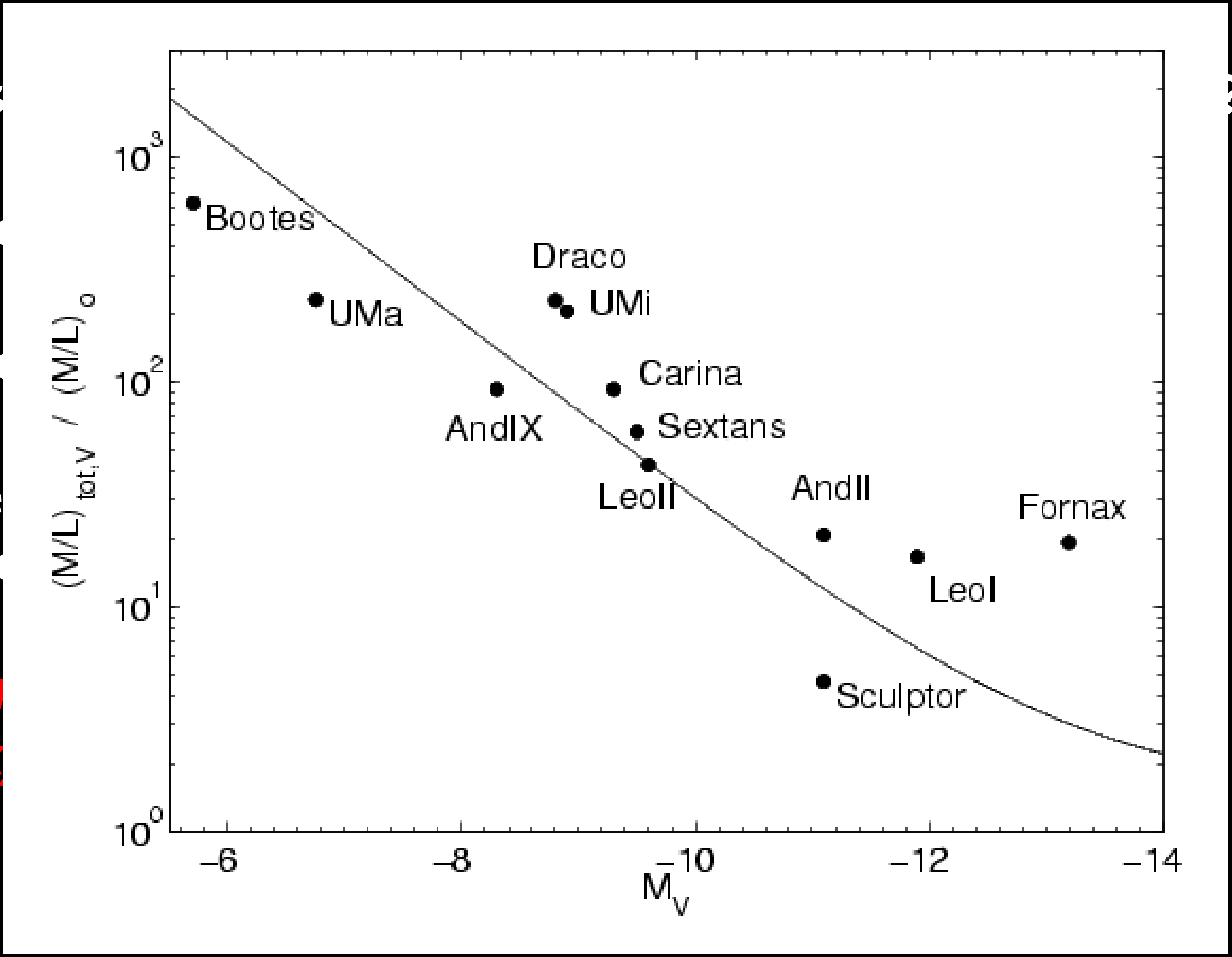
(1) What is … ?

(2) Why ar…

(3) Why ar…

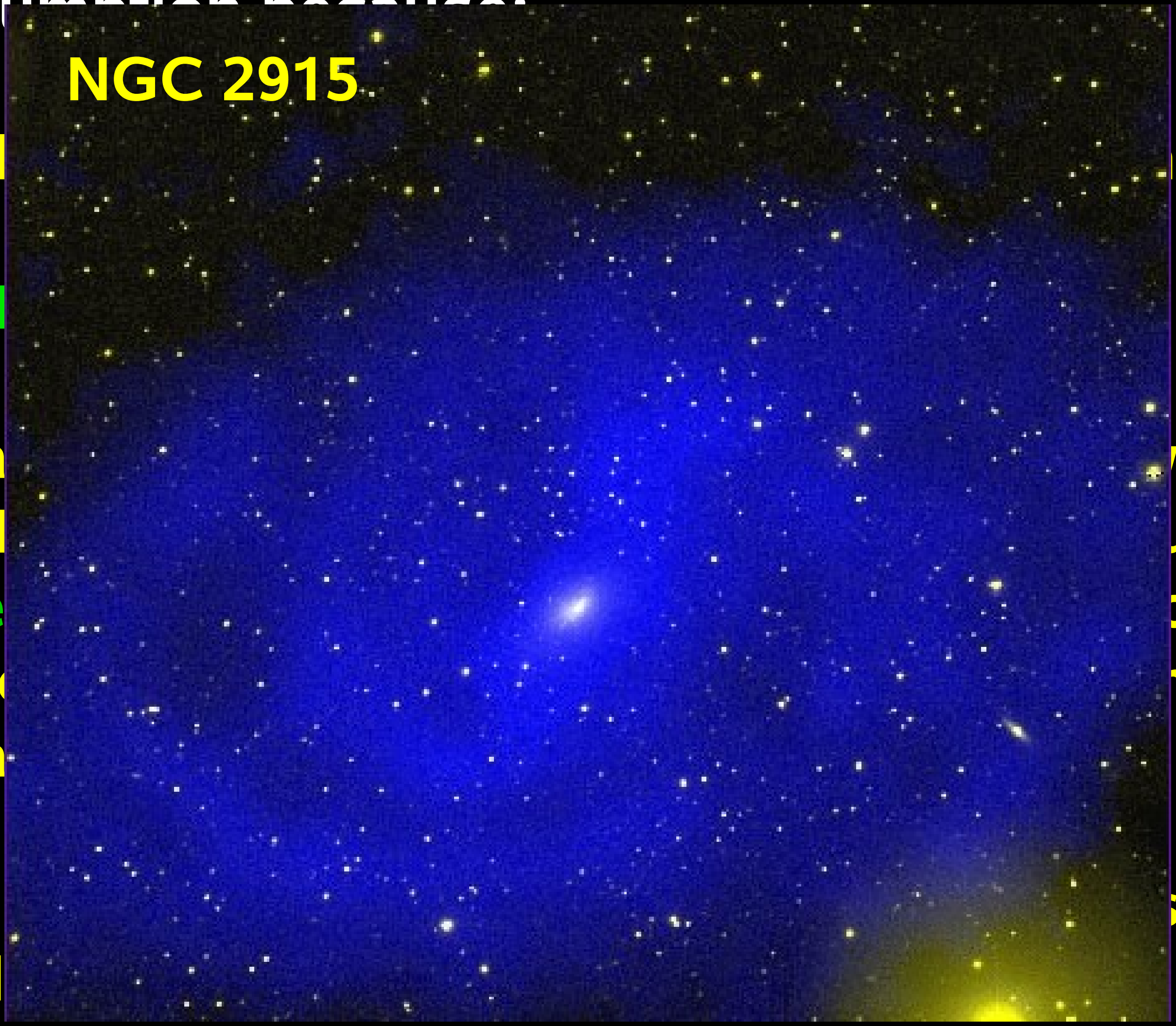
(4) Can we … by trying t…

(1) sug… of disk…



What if the progenitor was gas dominated?

Plausible ass



(3)Late-type d > 0.5
today (e.g. &
Moore 2004

(2)Simple ana arfs
should be T urface
density (Ve oomre
Q ~ 1 not n n
threshold a

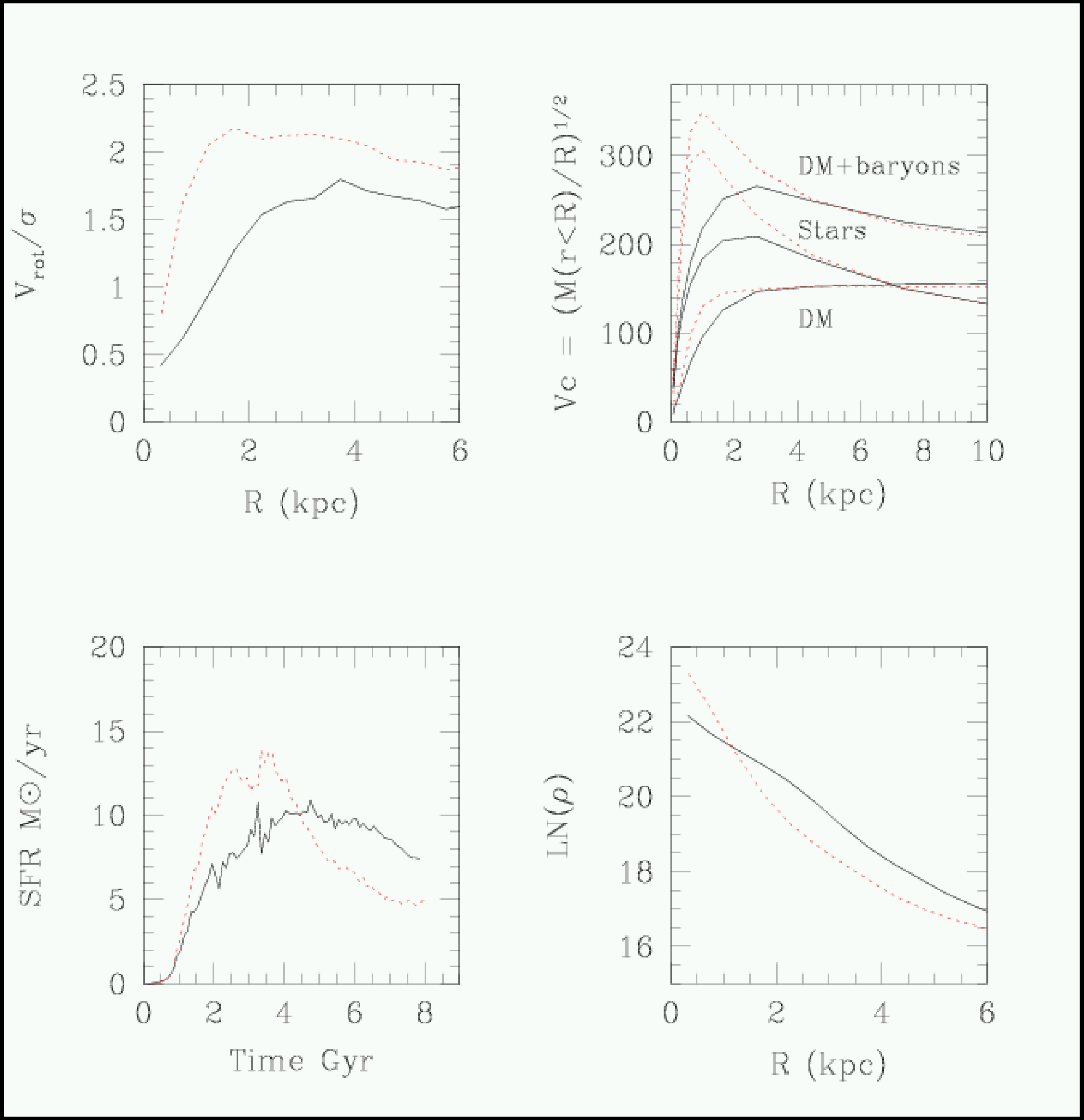
(3) Hydro sim ks
would pred rface
density, Q > 1.5 gas disk as that of dIrrs (Li, MacLow &
Klessen 2005; Robertson et al., in prep.)

Example of numerical effects due to limited resolution

Primary MW-sized halo

Artificial angular momentum loss (e.g. Kaufmann, Mayer et al. 2006)

Numerical effects X10 for satellites that have 100 times less particles than primary



TODAY's FOCUS: STRUCTURE OF SIMULATED GALACTIC DISKS

OUTLINE

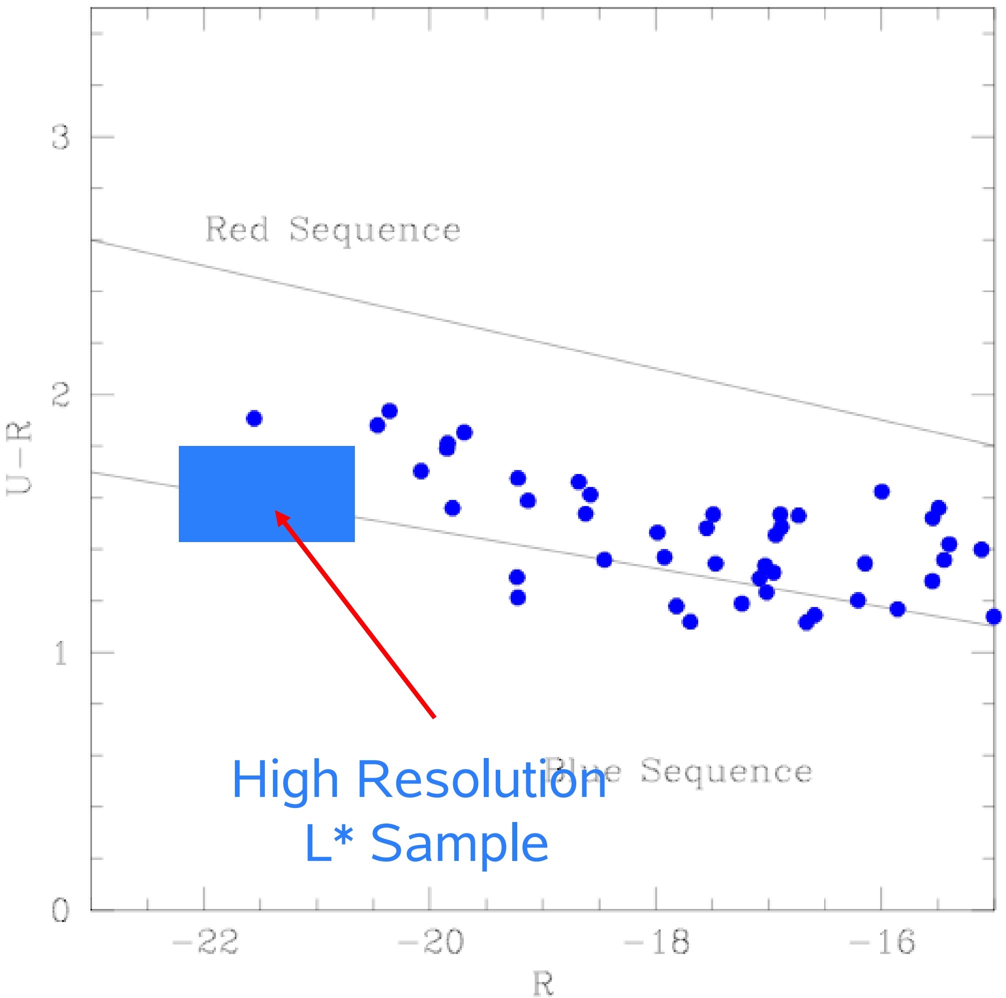
-- Brief overview: current status of cosmological simulations of galaxy formation.

Can we trust the current simulations? Are there numerical artifacts the standard technique, i.e. particle based (N-Body+ smoothed particle hydrodynamics (SPH)) simulations?

-- Non-cosmological models of galaxy formation: a new tool to test numerical effects at resolutions non accessible in a fully cosmological simulation

--New avenues for numerical modeling with SPH: gaseous halos around galaxies, thermal instabilities and clumpy gas accretion


The L* Sample.

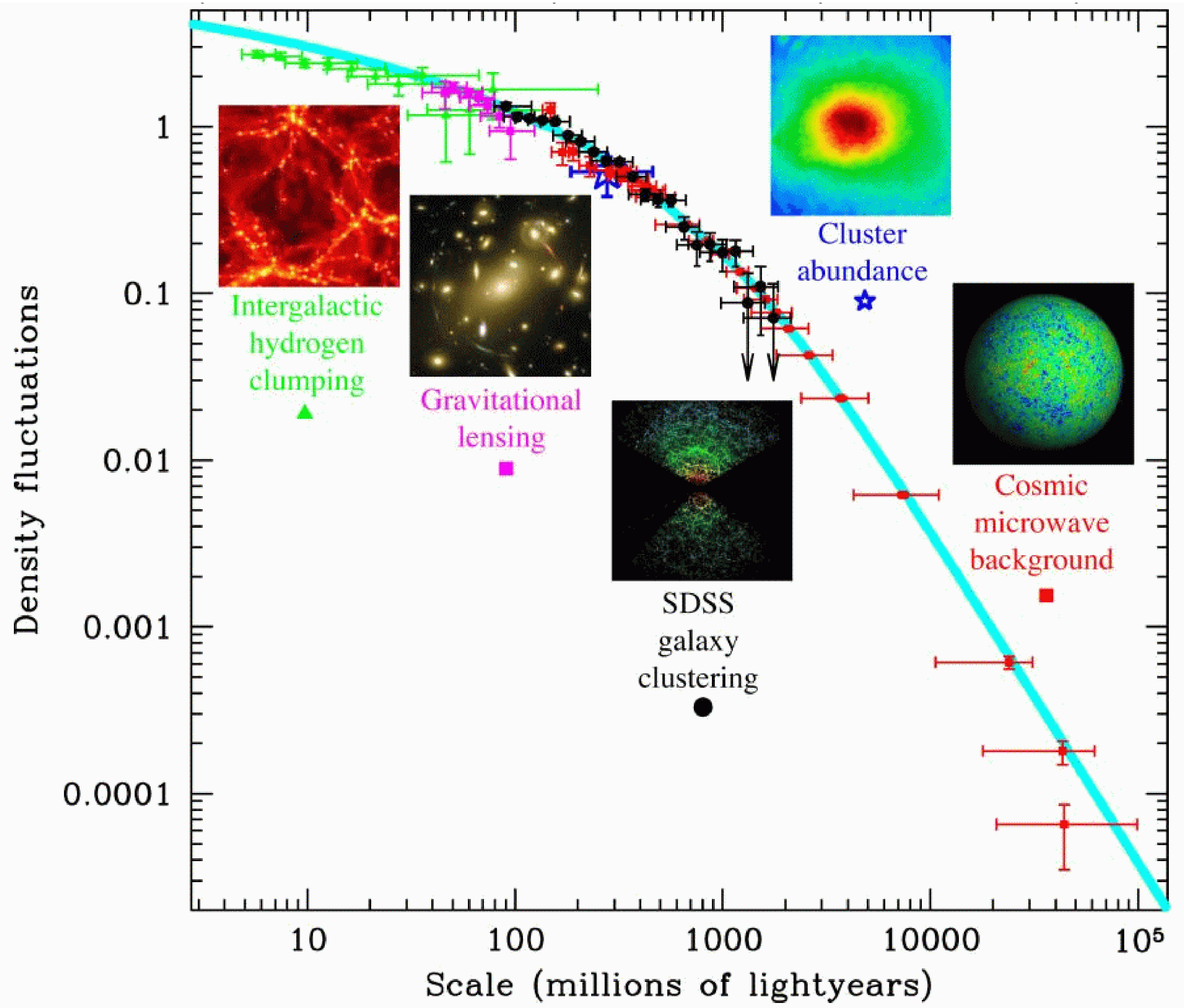


I Band Rds:
3 - 9kpc

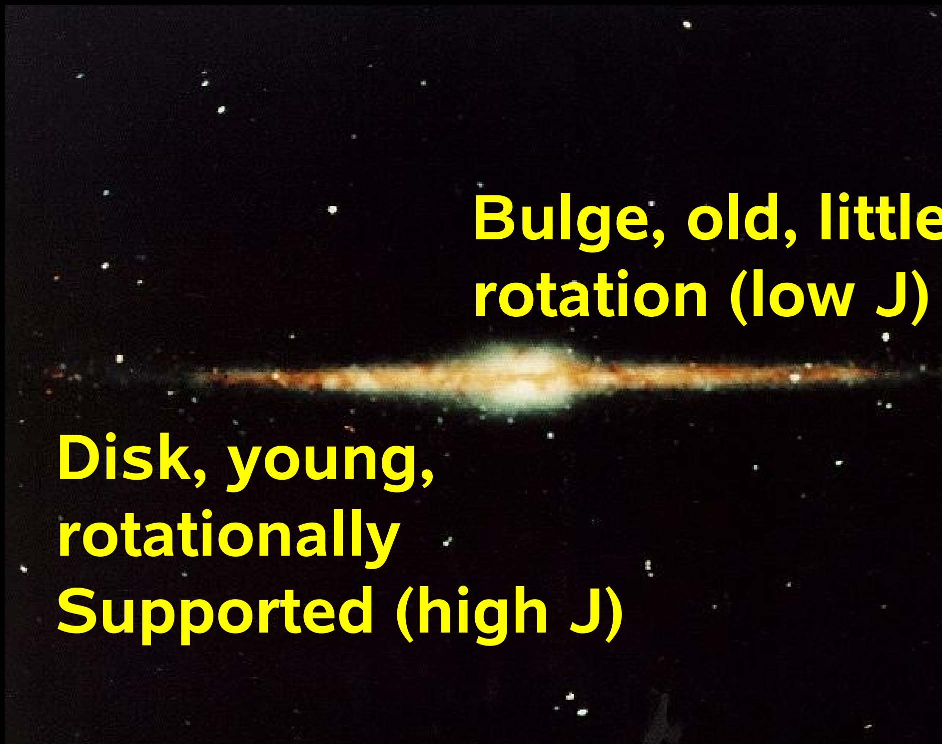
I band Bulge/Disk ratios
0.3 - 0.5

(reddened)

Observations of large scale structure of the Universe support power spectrum of density fluctuations predicted by ΛCDM model

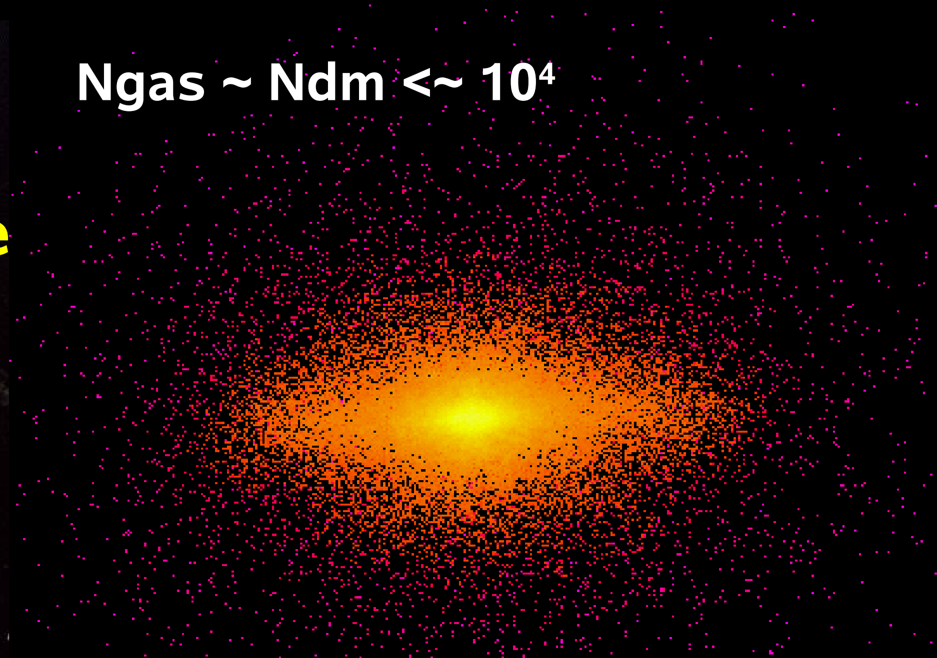


Disk formation in cosmological simulations: even bigger problems…



Milky-Way galaxy, NIR COBE image

Disk galaxies most common type of galaxies in the Universe



Simulated "disk" galaxy with mass of the MW (late 90s) in ΛCDM model.

Spheroidal rather than disky, baryons do not have enough angular momentum