# The formation of galaxies in the CDM Universe: successes and open issues across a range of mass scales

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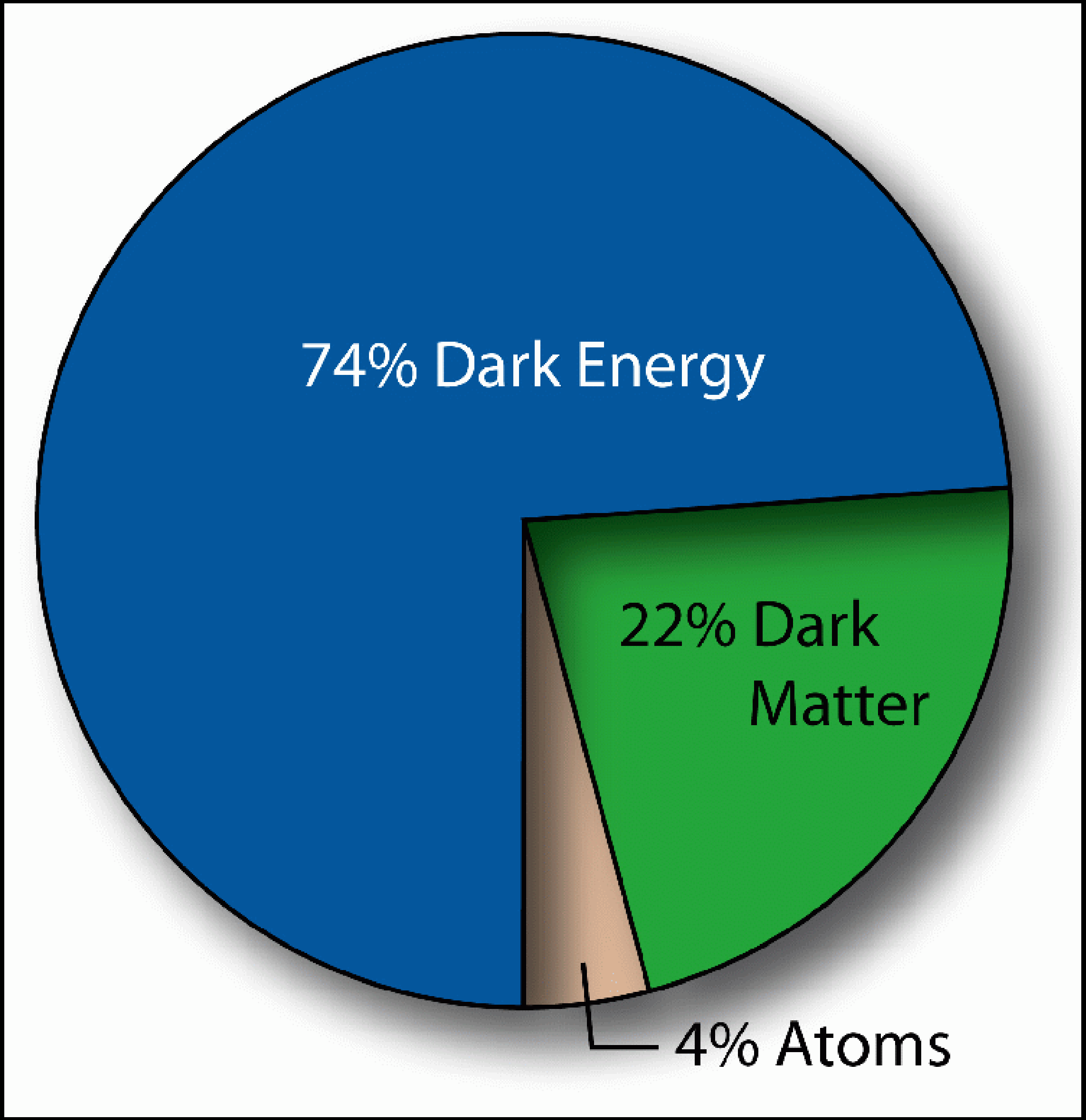
# The current cosmological paradigm: the $\Lambda$CDM model

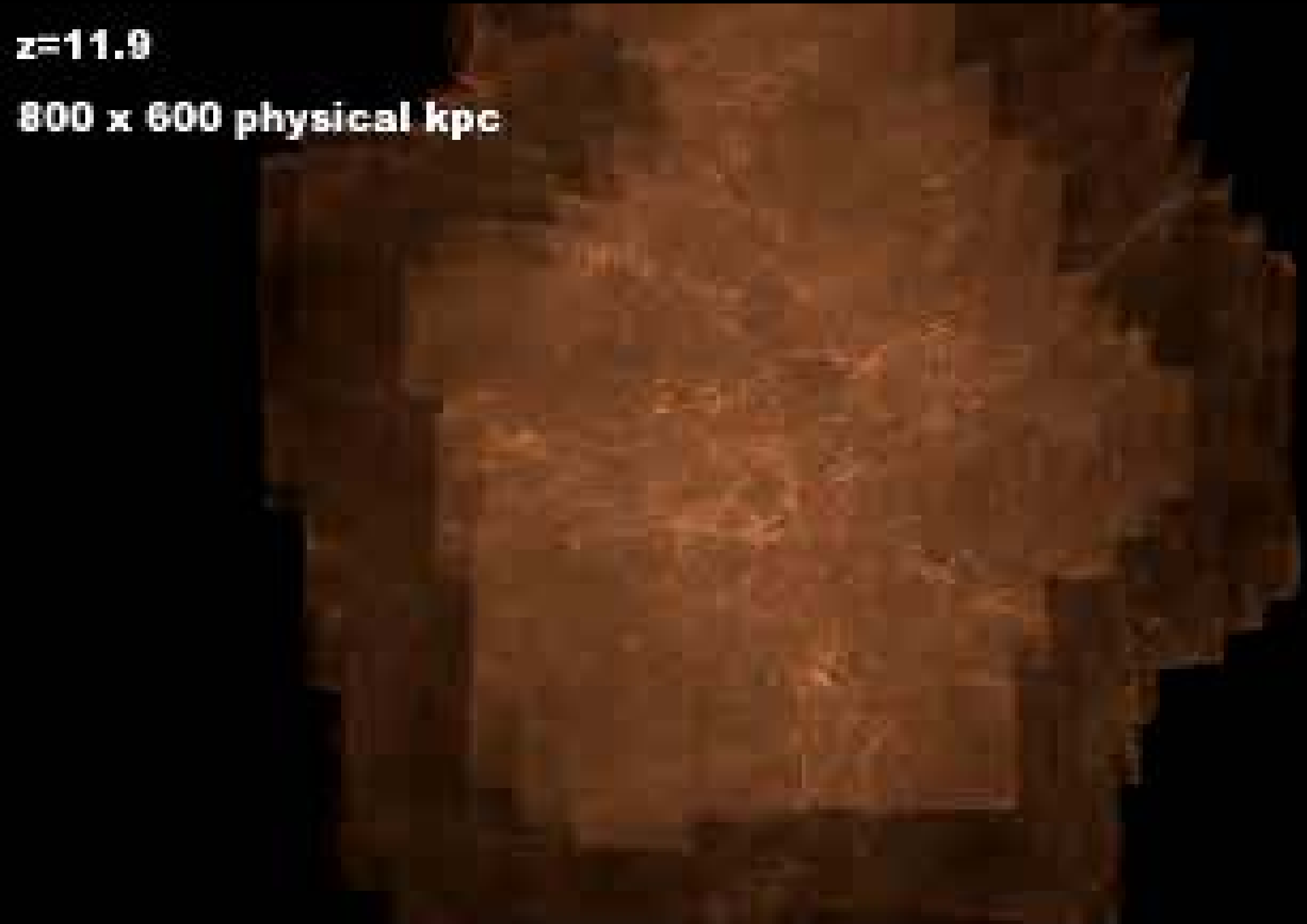



**Cold Dark Matter (CDM) = weakly interacting particles (e.g WIMPs) with negligible thermal velocity, dynamics dictated by gravity**

# In $\Lambda$CDM cosmology cosmic structure forms BOTTOM-UP: Gravity rules

**Primordial small matter density fluctuations amplified by gravitational instability in an expanding Universe**

**→ collapse into dark matter halos that then merge with other halos to form progressively larger halos**




**Formation of dark matter halo**

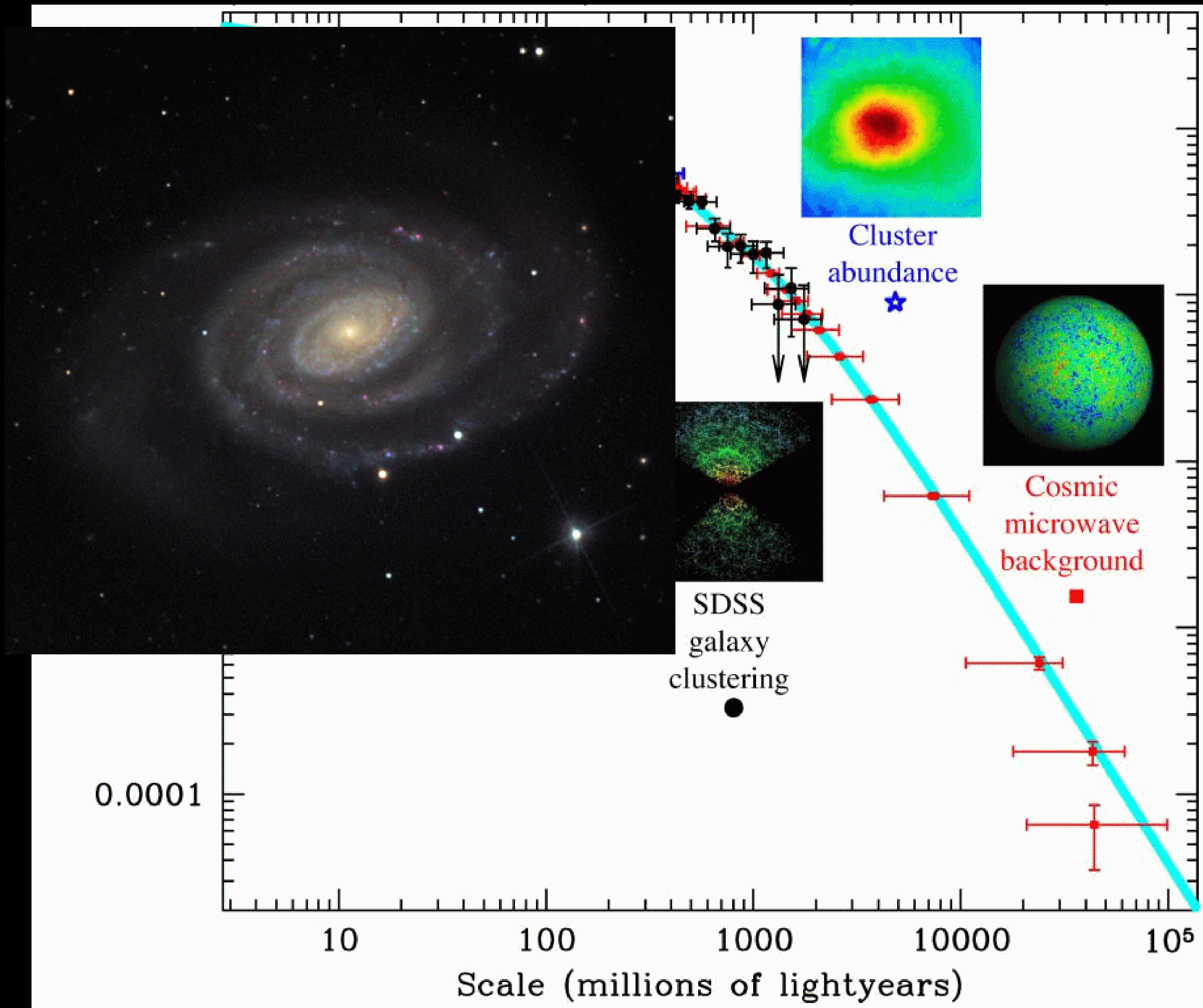
**N-Body code PKDGRAV2 (hierarchical tree method)**

**Periodic box**

**VIA LACTEA simulation (Diemand et al. 2007; 2008)**

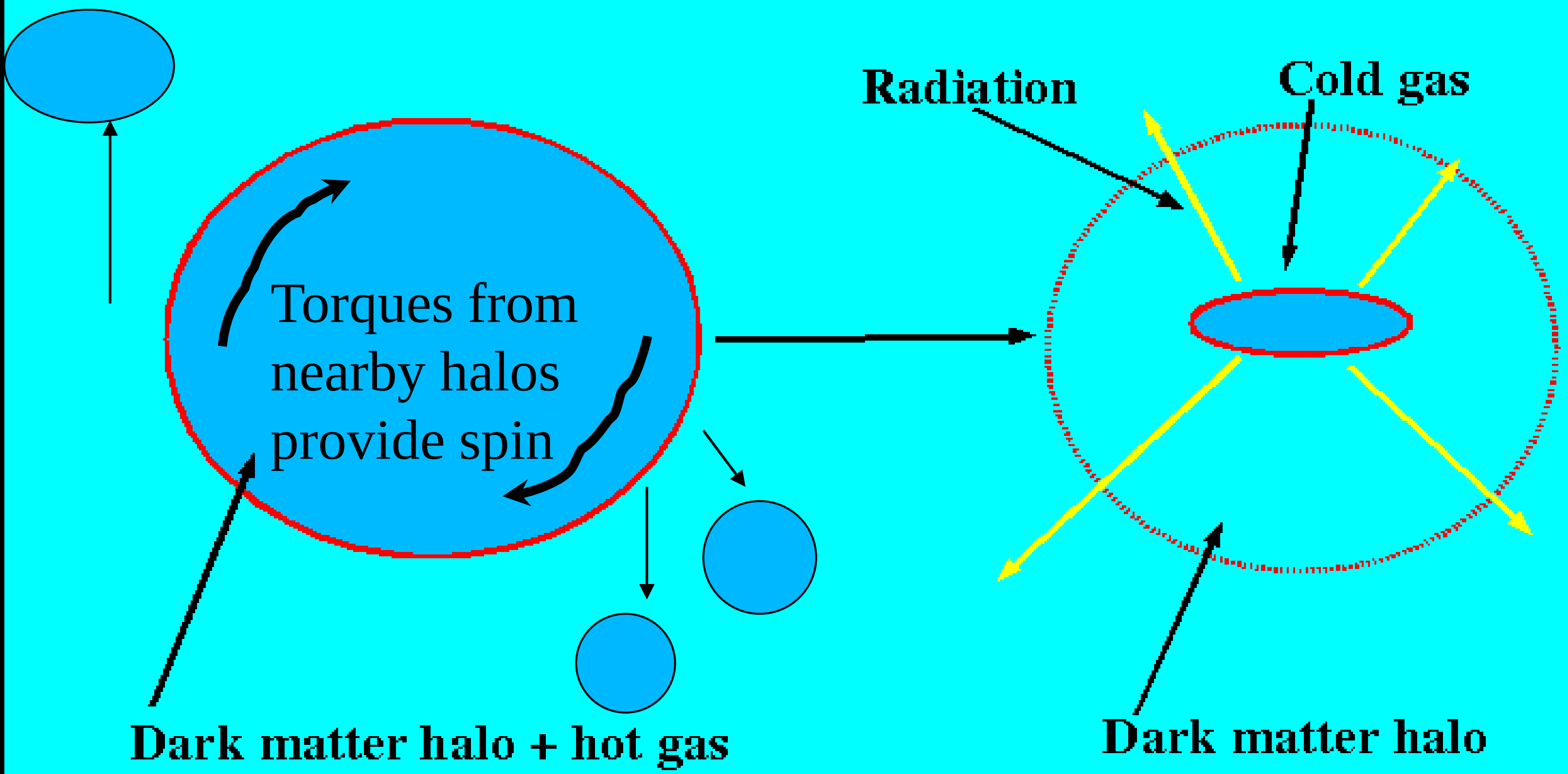
# Observations of large scale structure of the Universe support power spectrum of density fluctuations predicted by $\Lambda$CDM model

***But what about galactic scales ( < 100 kpc ~ $10^5$ light years)?***
***Can we reproduce observed galaxies in the $\Lambda$CDM model?***



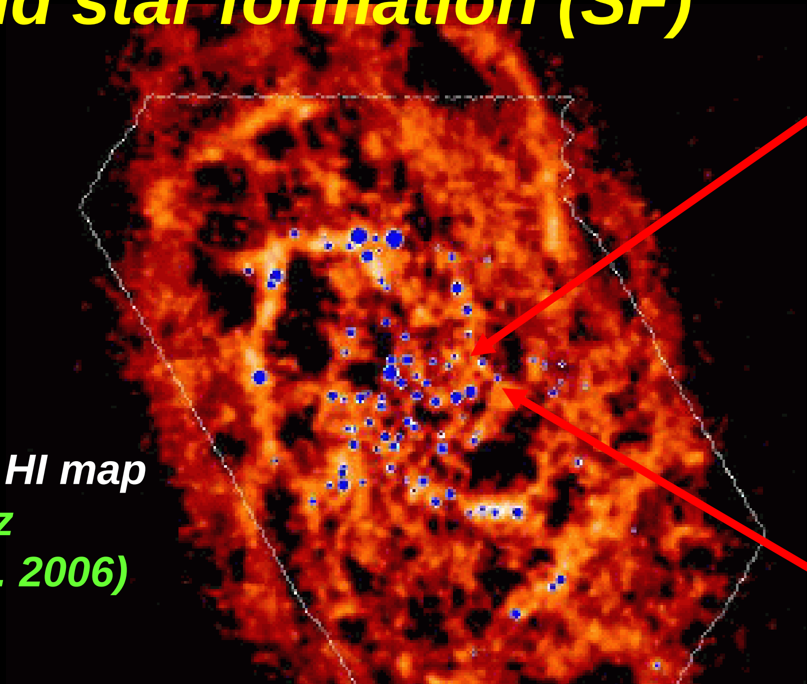
# Galaxy formation in CDM Universe: baryons in dm halos

- Hot baryonic plasma (H, He, T ~ $10^5$-$10^6$ K) falls into gravitational potential of dm halo
- Radiatively cools within halo ($T_{cool} \ll T_{hubble}$, *by recombination + radiative transitions)*
- Spinning disk form - gas settles at radius of centrifugal equilibrium because both gas and dark matter have angular momentum (from tidal torques)
- Gas disk forms stars out of the cold gas phase (Jeans unstable gas clouds)
- Stars reheat the gas via their radiation and supernovae exposions ("feedback")




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

# Complexity: *Physics of the interstellar medium (ISM) and star formation (SF)*



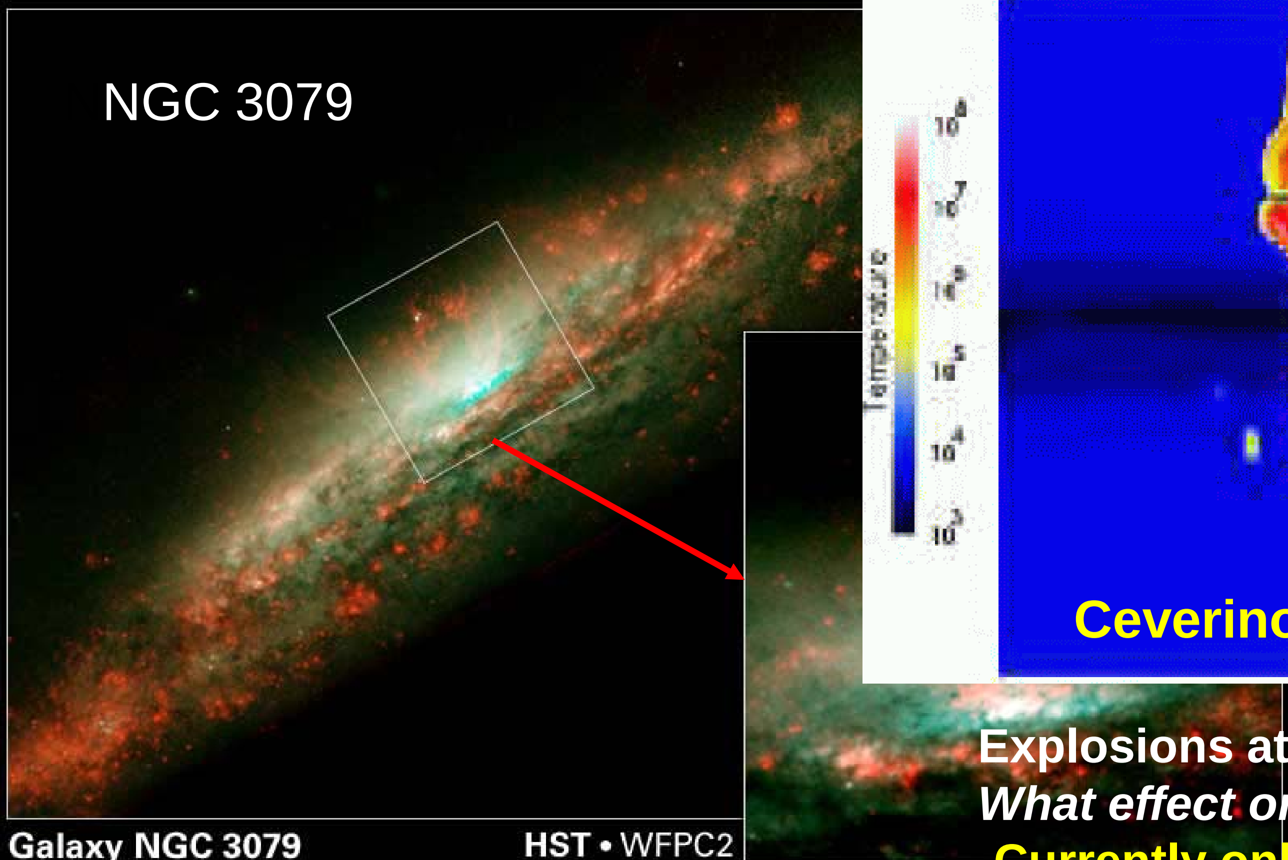
*M33 HI map (Blitz et al. 2006)*

**Physics known (baryons -- hydrodynamics, gravity, radiative mechanisms, magnetic fields) but two issues for modeling**

- **Multi-scale (< 1 pc to 1 kpc) – resolution of numerical models of cosmic structure formation was only ~ 1 kpc till 2004, <100 pc today**

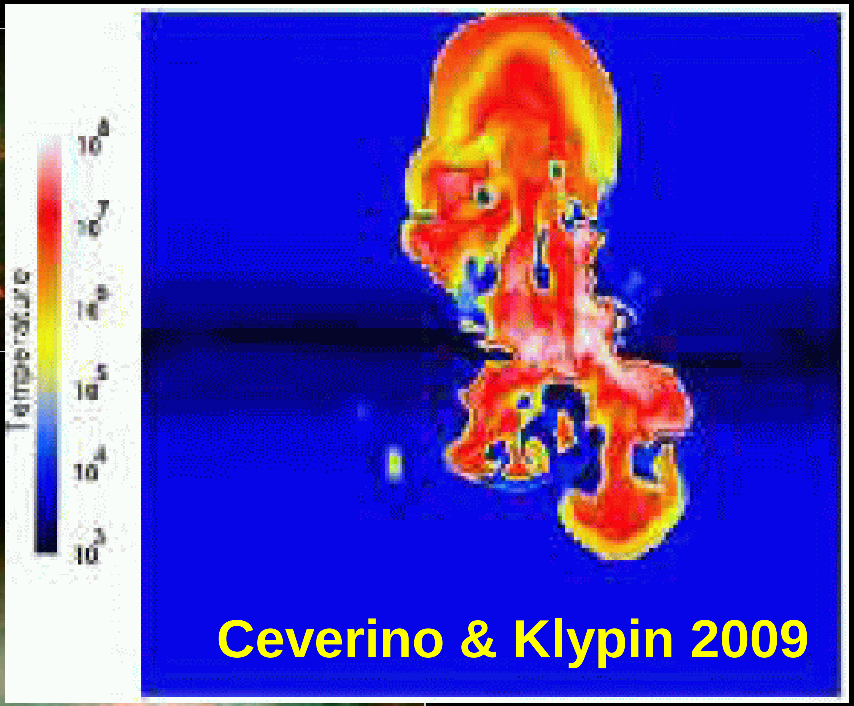
- **Multi-process: cooling, heating, phase transitions (e.g. from HI to $H_2$), star formation, stellar explosions, self-gravity, MHD phenomena, viscous phenomena (what source of viscosity?). Some of these processes not completely understood plus require interplay between many scales**

# Energy balance in the ISM; injection of energy by supernovae explosion (supernovae feedback)




**Galaxy NGC 3079** **HST** • WFPC2

NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28



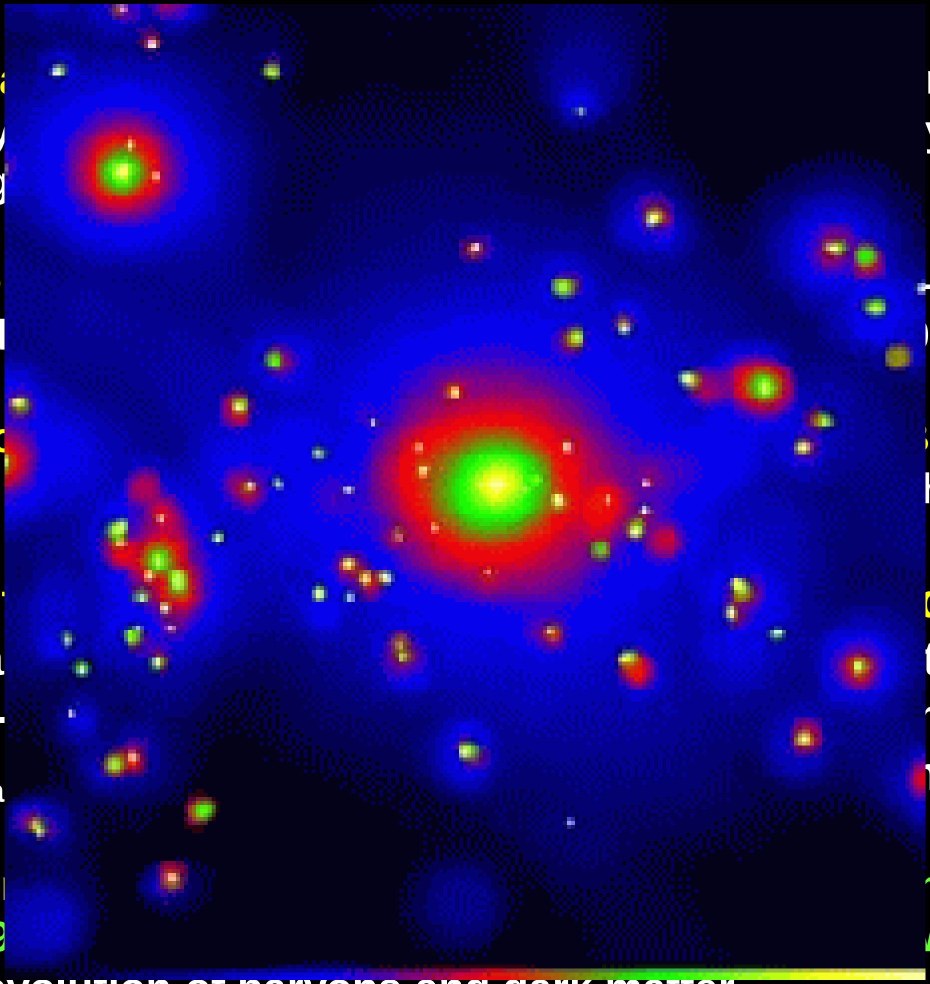

- **Maintain hot intercloud medium (HIM) ($f_V$~ 0.5, T > $10^5$ K, $\rho < 10^{-2}$ atoms/cc)**
- **Observed to drive "bubbles" and "winds" on scales of 100 pc to 1 kpc**

**Explosions at sub-pc scales**

***What effect on 100 pc scales?***

**-Currently only local calculations (volume < 100 pc) can model directly the hydrodynamics and thermodynamics of supernovae blastwaves**

**Tool for galaxy formation:** simulation with three-dimensional algorithms that solve for the coupled gravitational dynamics of the dissipationless cold dark matter component and the gravitational and radiative hydrodynamics of the dissipative baryonic fluid



▪Self-gravit ... rned by Euler equation
+ continuity ... y equation with cooling
and heating

▪SUB-GRID ... - star clusters form in
coldest and ... $^5$ Mo).

▪In early mo ... -GRID feedback - transfer
fraction of ... hermal energy (no wind/bubble)

Research ... d codes
because a ... turally adaptive in space
and time - ... mic structure
(in MW $\rho_{ha}$ ... ms/cm$^3$).

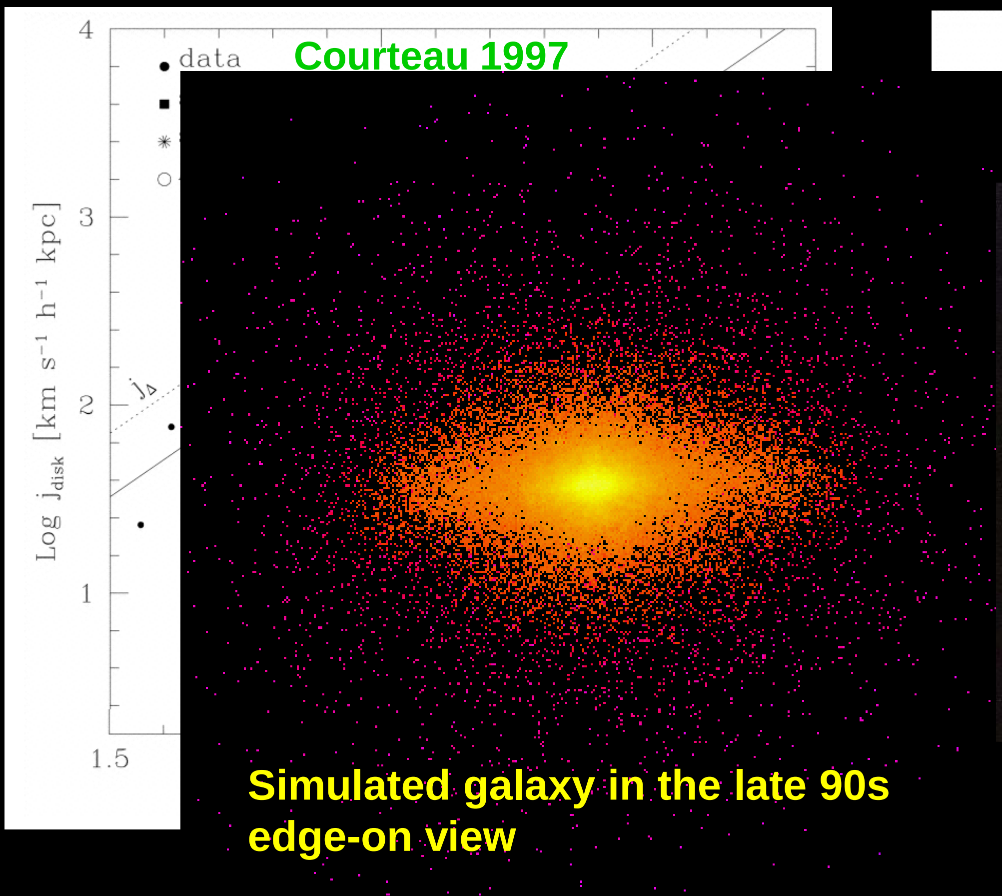
N-Body + S ... nquist & Katz 1989; Navarro
& Benz 199 ... Wadsley et al. 2004)
Follow co-evolution of baryons and dark matter

Dense “baryonic cores” (yellow) form at the center of dark matter halos as a result of cooling

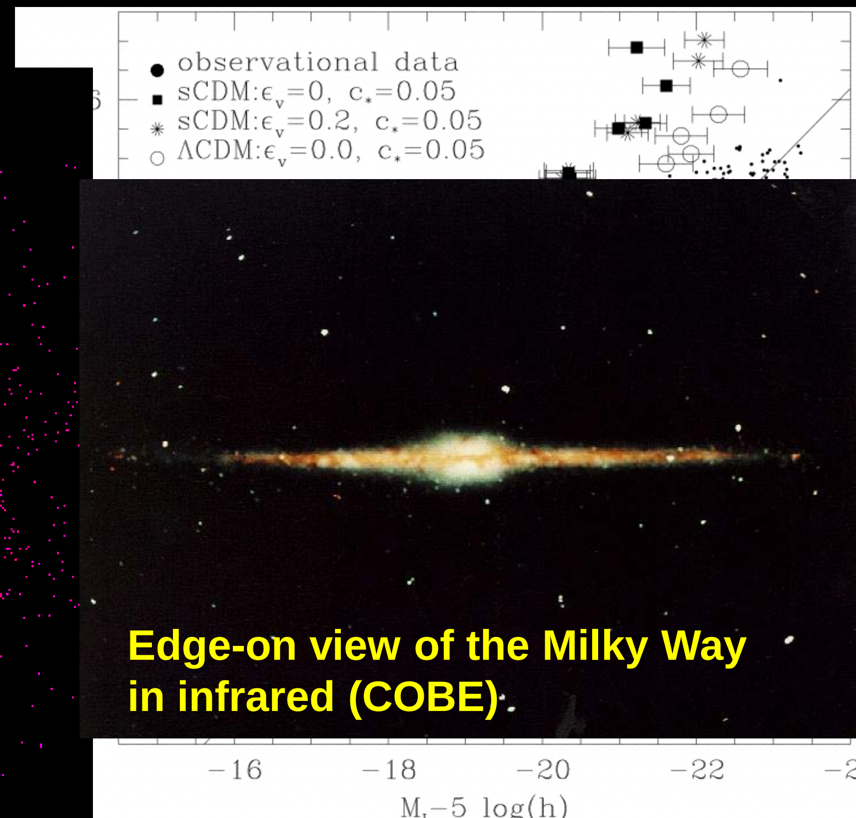
# Simulated galaxies: Angular Momentum Problem

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

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




Simulated galaxy in the late 90s edge-on view




Edge-on view of the Milky Way in infrared (COBE)

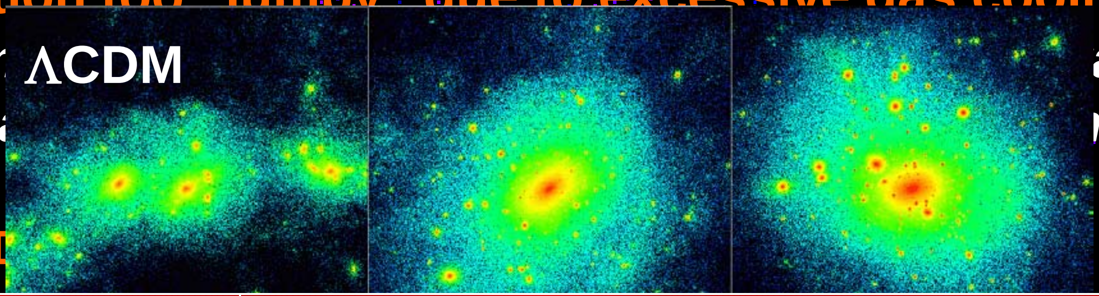
*Navarro & Steinmetz 2000*

Both in observations and simulations $J_{disk} \sim R_{disk} * V_{rot}$, where $R_{disk}$ is computed by fitting an exponential profile to the stellar surface density

# Is galaxy formation CDM model-compatible?

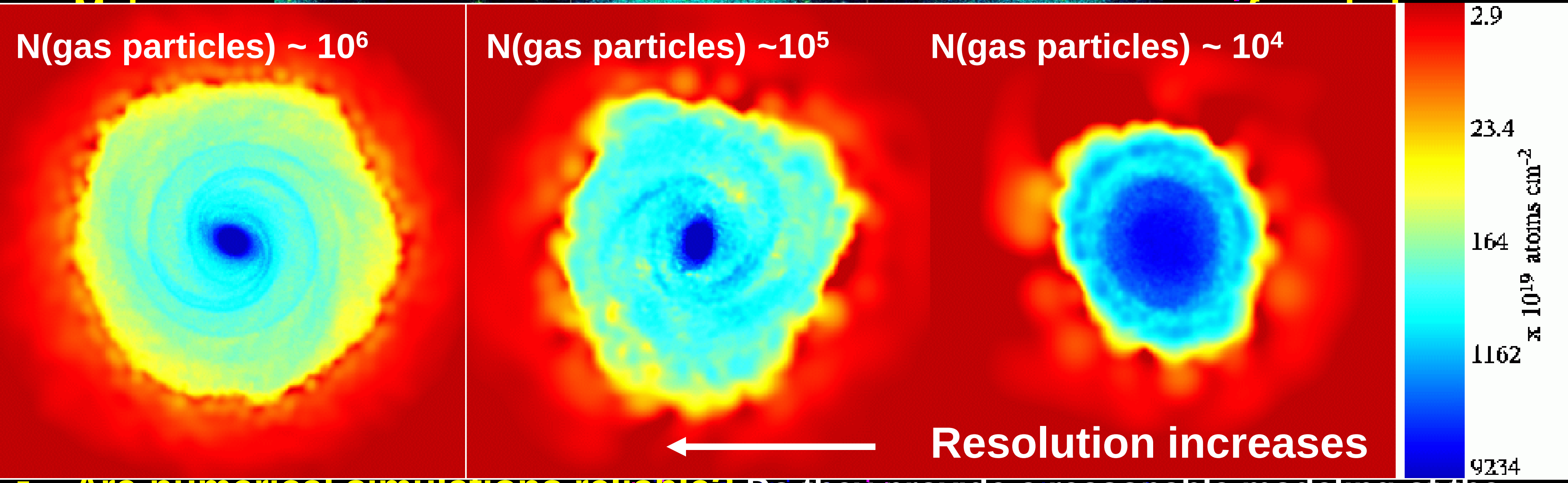
**Original interpretation of angular momentum problem**

**(Navaro & Benz 1991, Navarro & White 1994):**

**gas distribution too “lumpy” due to excessive gas cooling -→ *dense lumps of dm*** 

***ag (“dynamical friction”) a*** ***disk***

**PROPOSED**

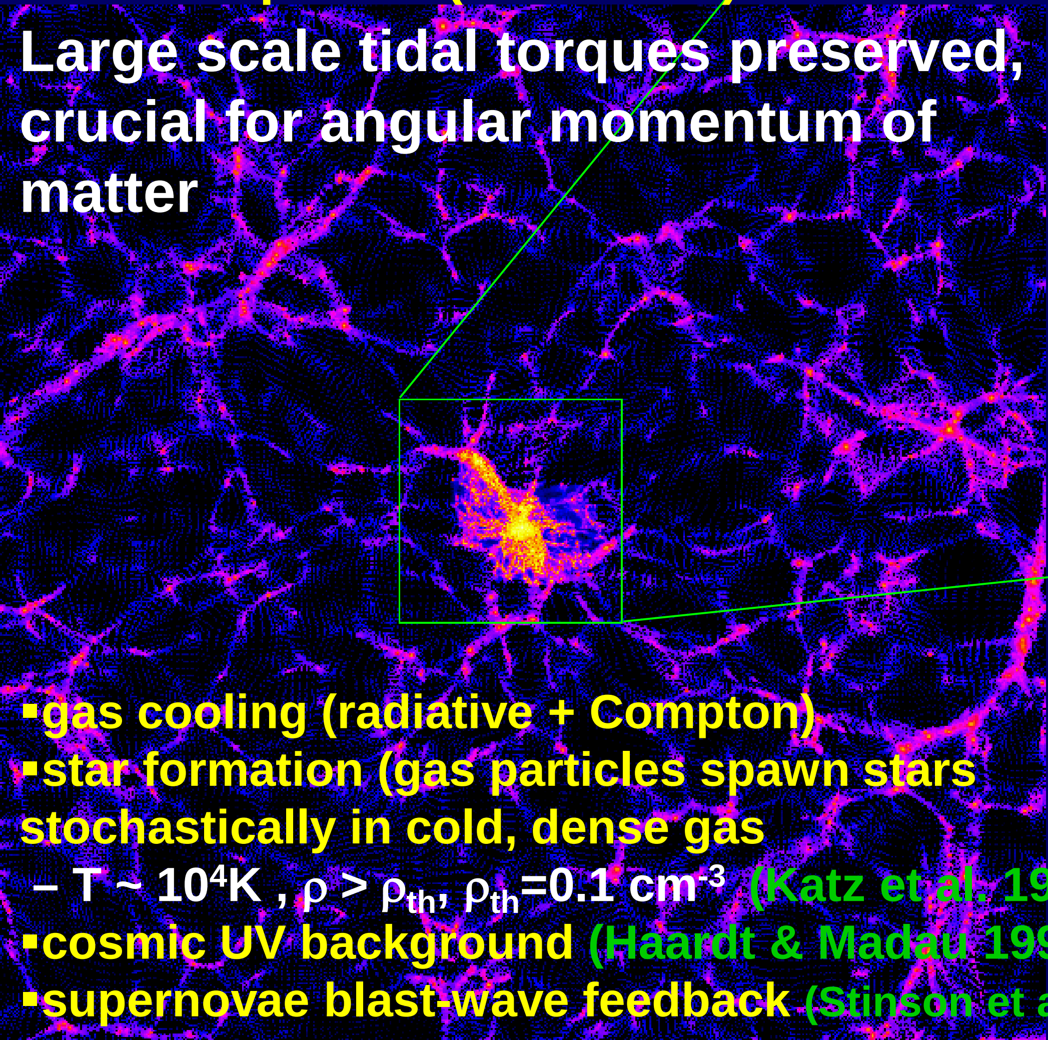


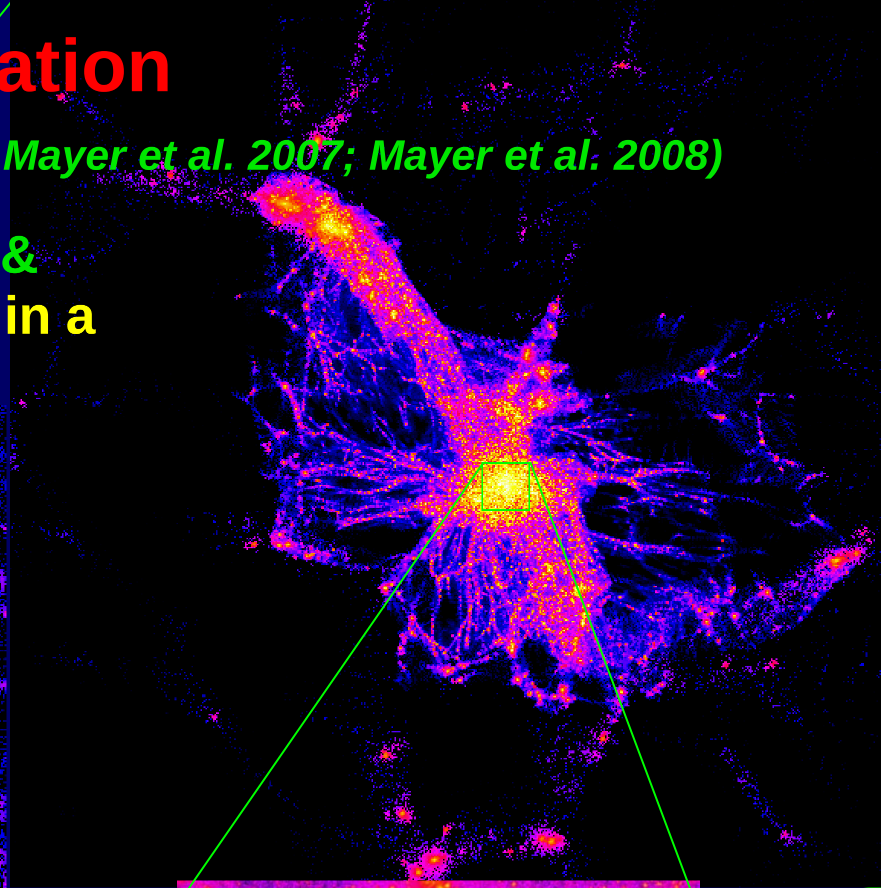

- **Are numerical simulations reliable?** **Do they provide a reasonable modeling of the physical processes at play? We found numerical resolution is a major issue; with less than a million resolution elements per galaxy spurious loss of angular momentum**
**(Mayer 2004; Kaufmann, Mayer et al. 2007; Mayer et al. 2008)**

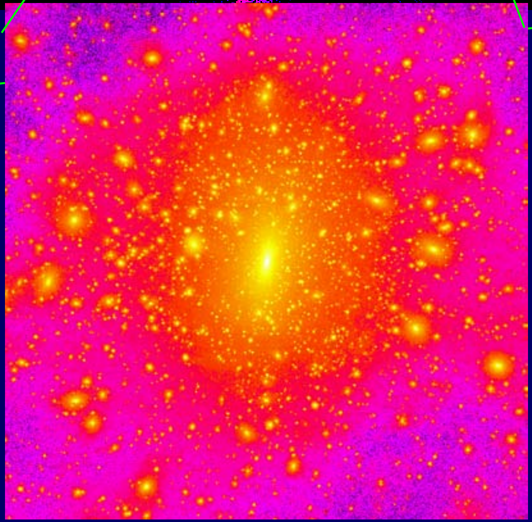
# High resolution galaxy formation

*(Governato, Mayer et al. 2004; Governato, Willman, Mayer et al. 2007; Mayer et al. 2008)*

**Multi-mass refinement technique (Katz & White 1993): < 1kpc spatial resolution in a 50-100Mpc box (DM + GAS)**







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

- **gas cooling (radiative + Compton)**
- **star formation (gas particles spawn stars stochastically in cold, dense gas – $T \sim 10^4$K , $\rho > \rho_{th}$, $\rho_{th}$=0.1 cm$^{-3}$ (Katz et al. 1996)**
- **cosmic UV background (Haardt & Madau 1996)**
- **supernovae blast-wave feedback (Stinson et al. 2006)**

**SUB-GRID Supernovae Feedback : cooling stopped in region heated by supernovae blastwave for $t_s \sim 30$ million years**

- *Based on time of maximum expansion of supernova blast wave (Sedov-Taylor phase + snowplaugh phase). Radius of blastwave self-consistently calculated based on McKee & Ostriker (1977)*
- *Blastwave generated by simultaneous explosion of many supernovae type II (time resolution limited as mass resolution – single star particle represents star cluster in which many type II supernovae can explode)*

**Dwarf galaxy (M ~ $10^{10}$ Mo)** **Milky Way-sized galaxy (M ~ $10^{12}$ Mo)**

- **Free parameters (SF efficiency and supernovae heating efficiency) fixed to C*= 0.05 and eSN=0.4 after calibration with isolated galaxy models to reproduce a range of properties in present-day galaxies across wide mass range (cold/hot gas volume ratio, gas turbulent velocities, disk thickness, star formation rates - see Stinson et al. 2006)**
- **Heating also by type Ia supernovae but without delayed cooling (no collective blastwave)**

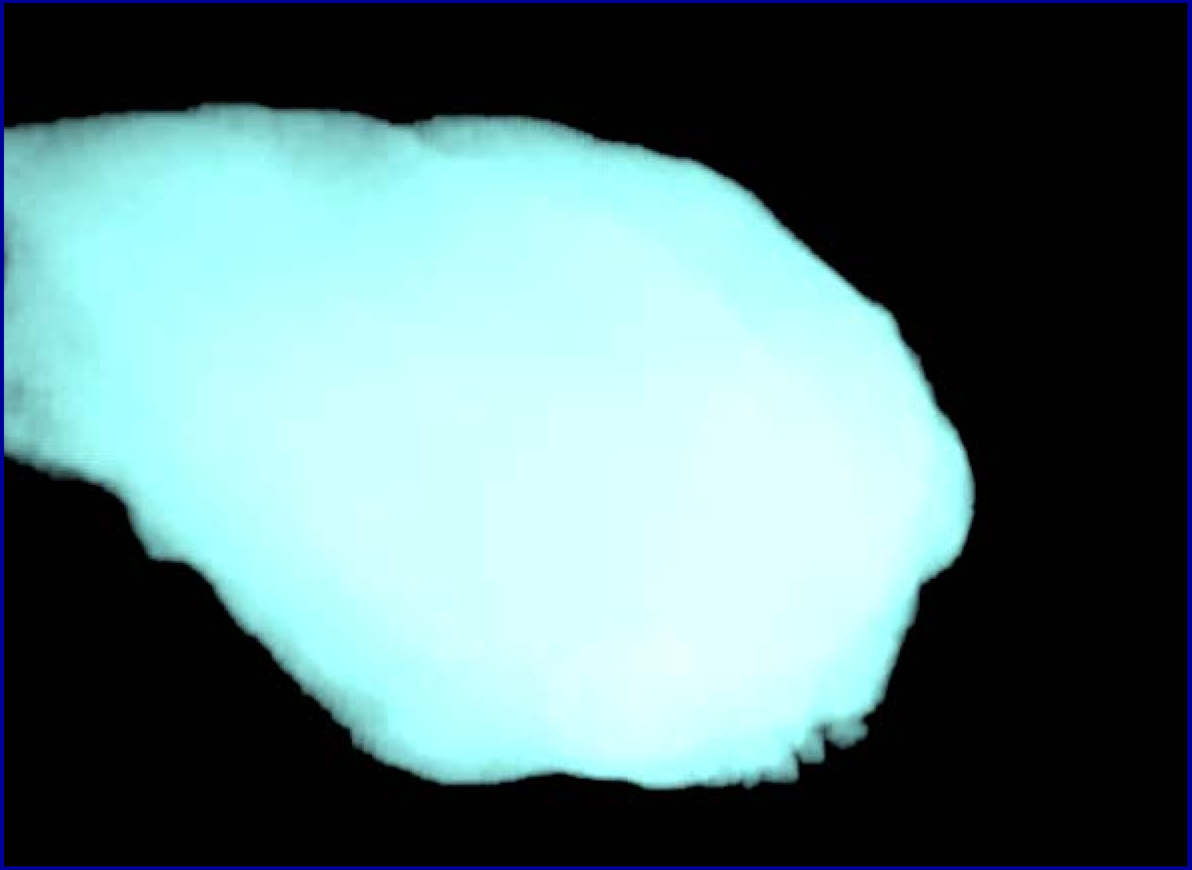
# Formation of Milky Way-sized galaxies

**(Ngas, Ndm ~ 1-3 x $10^6$ within R ~ Rvir, cooling, SF, blastwave feedback, UV bg)**

**5 sims**, ***$M_{halo}$ ~ 7 x $10^{11}$-1 x $10^{12}$ Mo***

***(Governato,Willman, Mayer et al. 2007)***
***Mayer, Governato and Kaufmann 2008;***
***Callegari, Mayer et al., in preparation)***

**WMAP3 cosmology**



***Shown "quiet" system (last major merger at z ~ 2)***

***Green=gas***

***Blue=young stars***

***Red=old stars***

**Frame size = 100 kpc comoving**

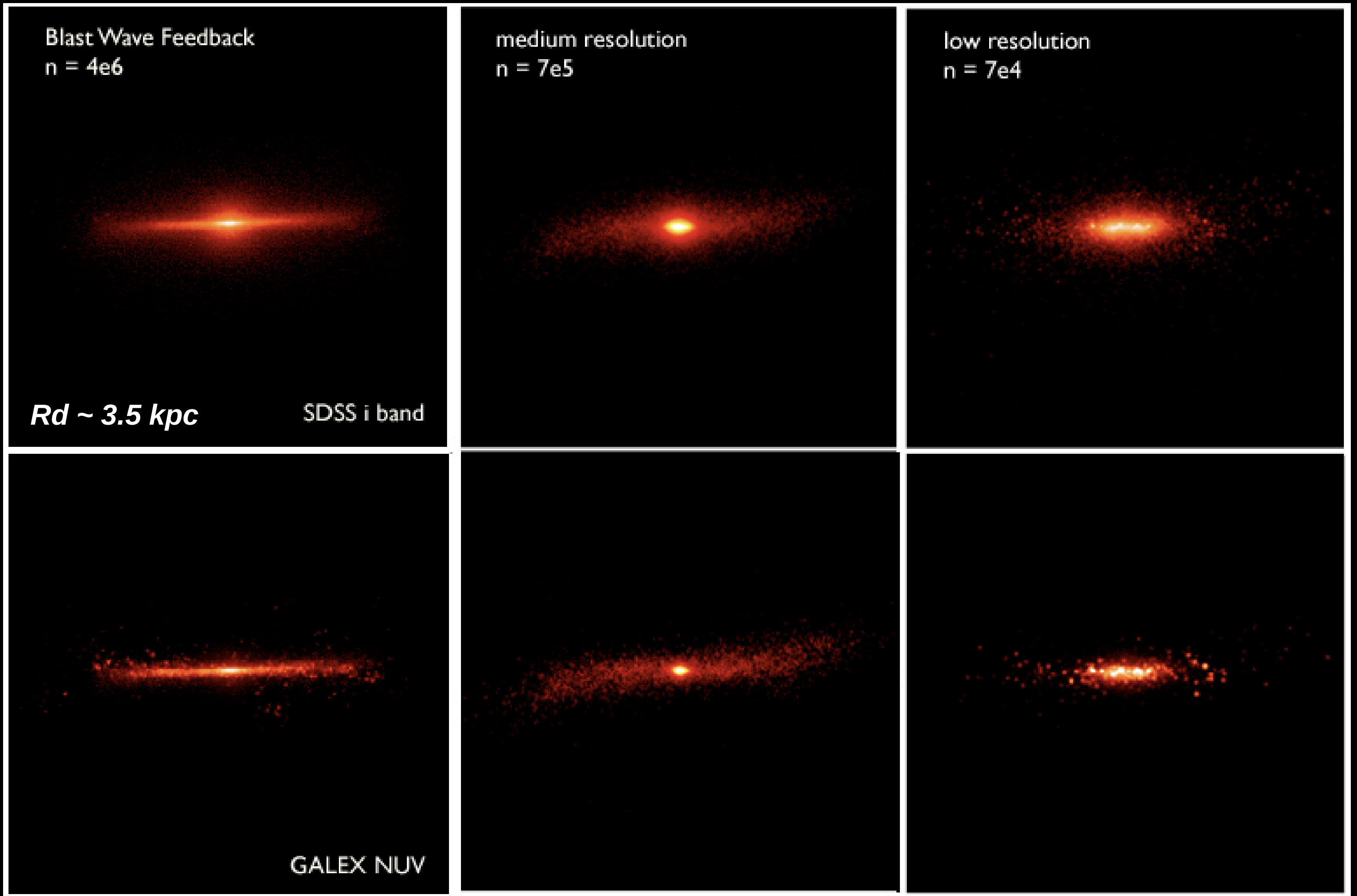
# Higher Resolution makes larger disks

See Kaufmann, Mayer et al.2007
Mayer et al. 2008

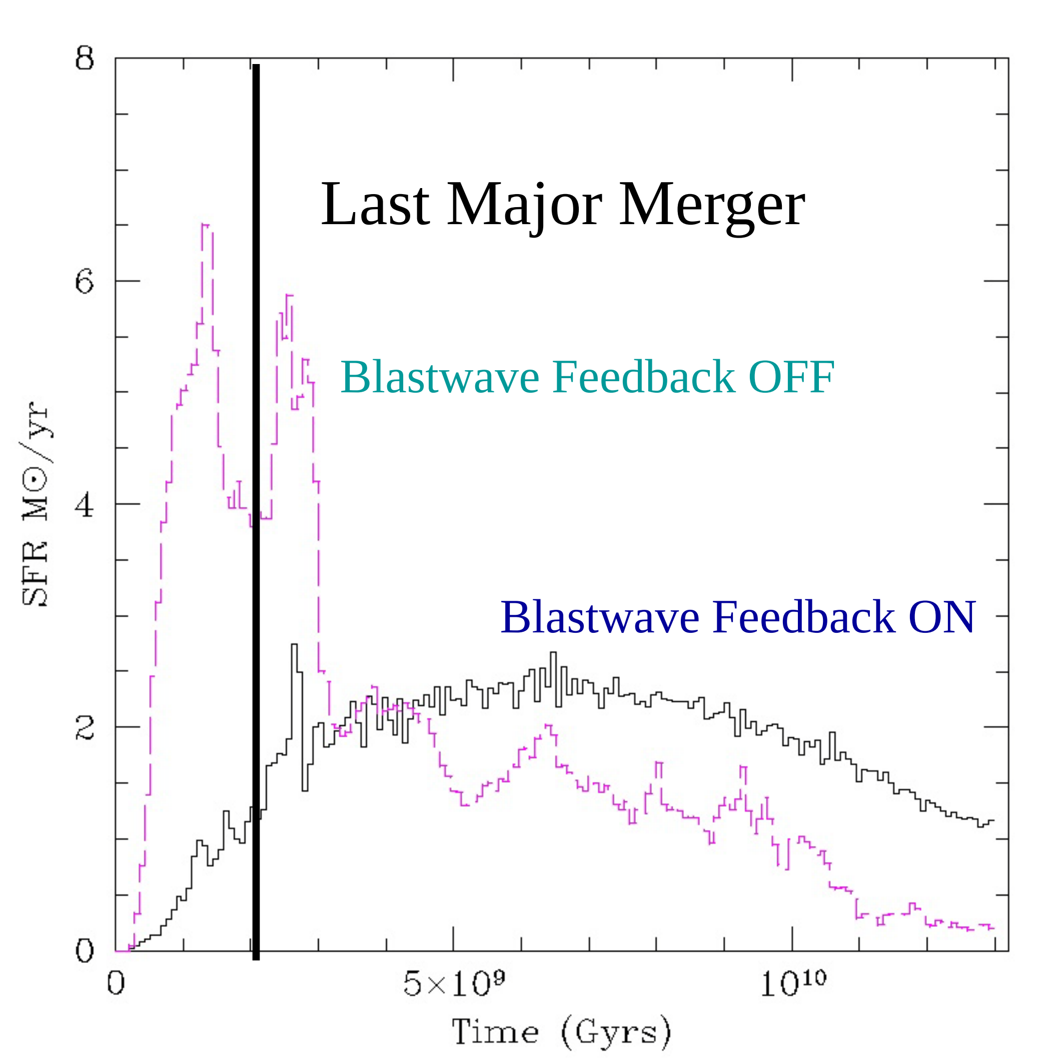
N=DM+Gas+stars

Images made with SUNRISE (P. Jonsson)

Boxes 50 kpc across



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



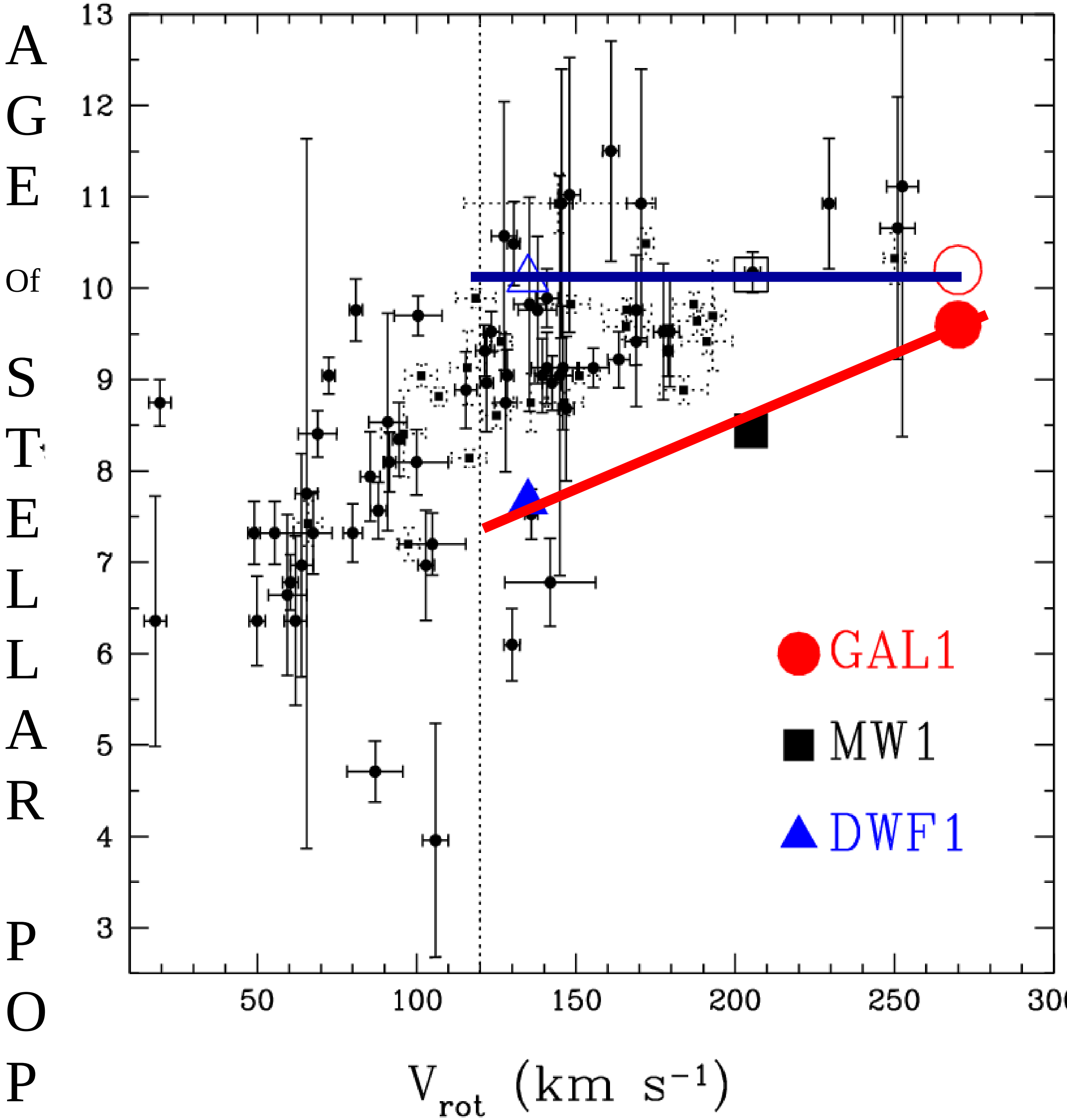

SFH includes all progenitors at any given time

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.*

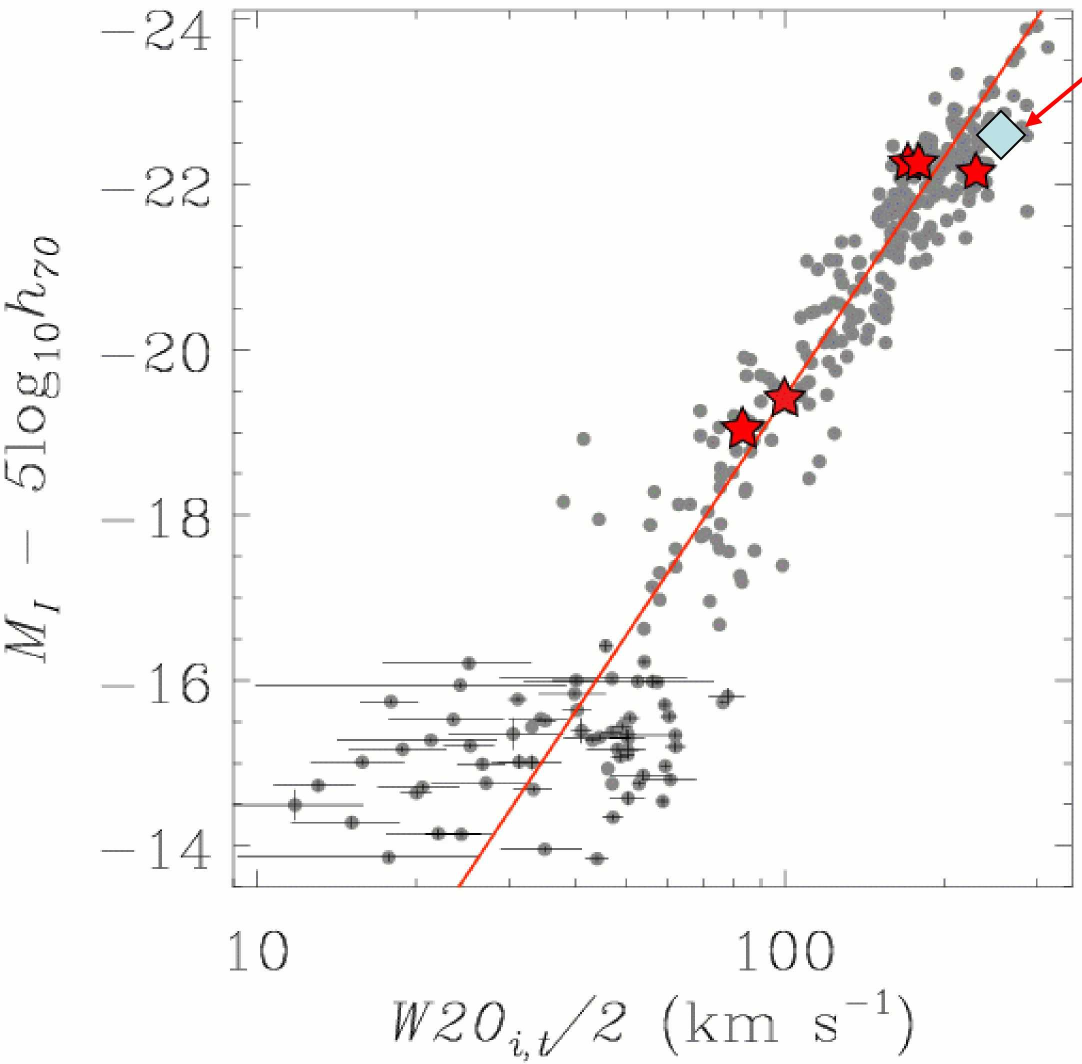
SF significantly reduced in early mergers due to feedback in progenitors




## Mac Arthur Courteau and Bell 2004

Runs with blastwave feedback reproduce the observed Vrot vs Age trend.

Star Formation delayed/suppressed in small progenitors.




**One simulated with AMR code RAMSES w/same sf/feedback model (Teyssier et al. 2009)**

### 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).

**Simulated galaxies are usually chosen with quiet merging history, e.g. no major mergers after z = 1.5-2 (e.g. Abadi et al. 2003; Mayer et al. 2008; Scannapieco et al. 2008;2009), choice biased by evidence coming from the Milky Way**
**-→ *favourable case to preserve large disk because galaxy collision would turn the disk into a hot spheroid (Barnes & Hernquist 1996).***

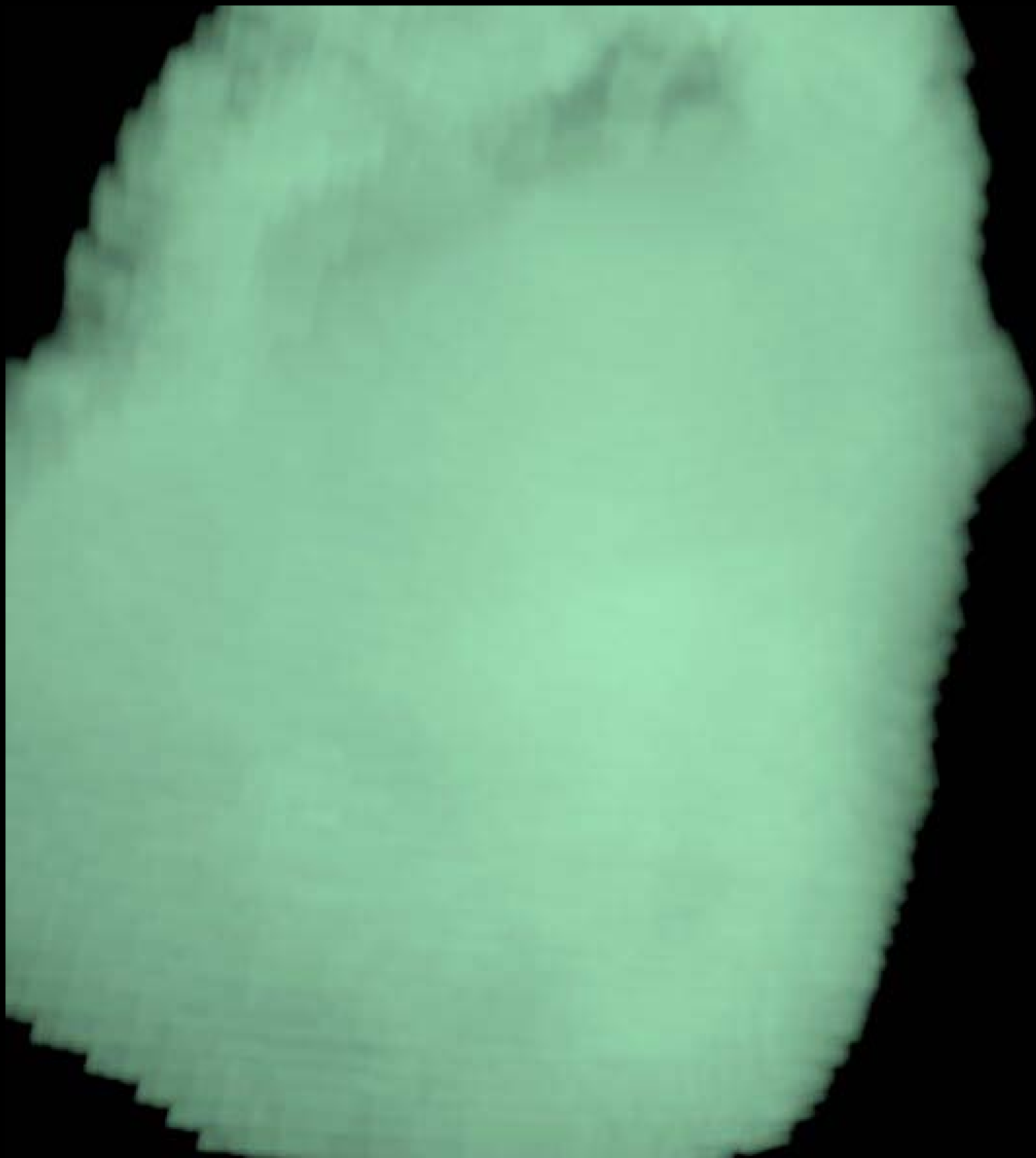
**But at least 1 major merger quite common for $10^{12}$ Mo halos at z < 1 (Stewart et al. 2008)**

- ***Are major mergers a problem for the formation of a disk-dominated galaxy (> 50% of the galaxy population) ?***
- ***Is a quiet merging history a pre-requisite to form them within the context of CDM – a new issue?***

# Formation of a large disk galaxy from a gas-rich merger (Governato, Brook, Brooks, Mayer et al. 2009)

MW-sized galaxy ($M_{vir}$ ~ 7 x $10^{11}$ Mo)
Box is 100 kpc on a side

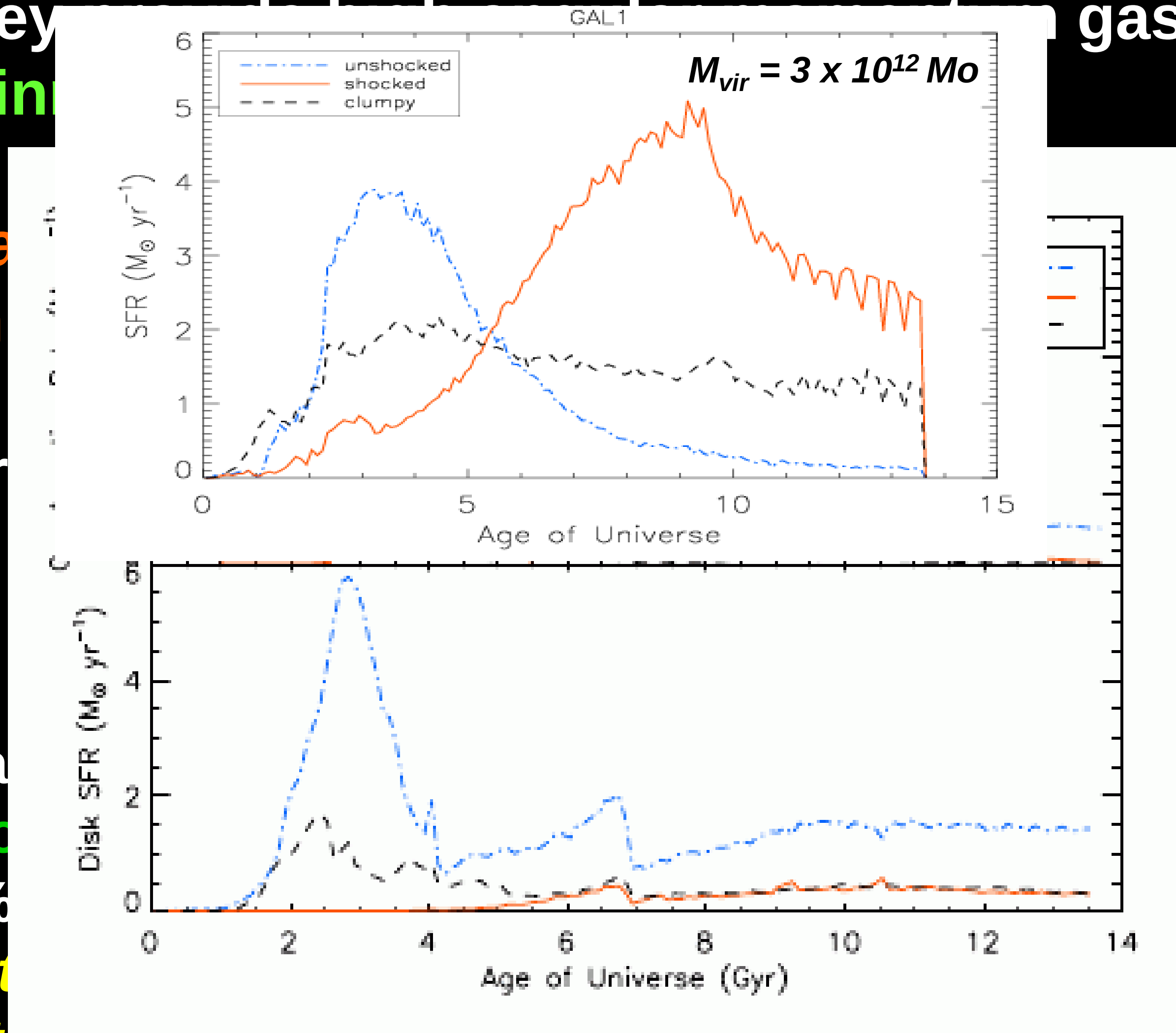
Last major merger z ~ 0.8
Moderately gas-rich merger (gas is ~15-20% of baryonic mass in disks)



▪**Gas-rich major mergers can build large disk galaxies because they** … **gas** **(Quinn & Bin**…

**-→ Orbital a** … **lar momentum** …

▪**Disk re-for** … **Keres et al. 2002;** …

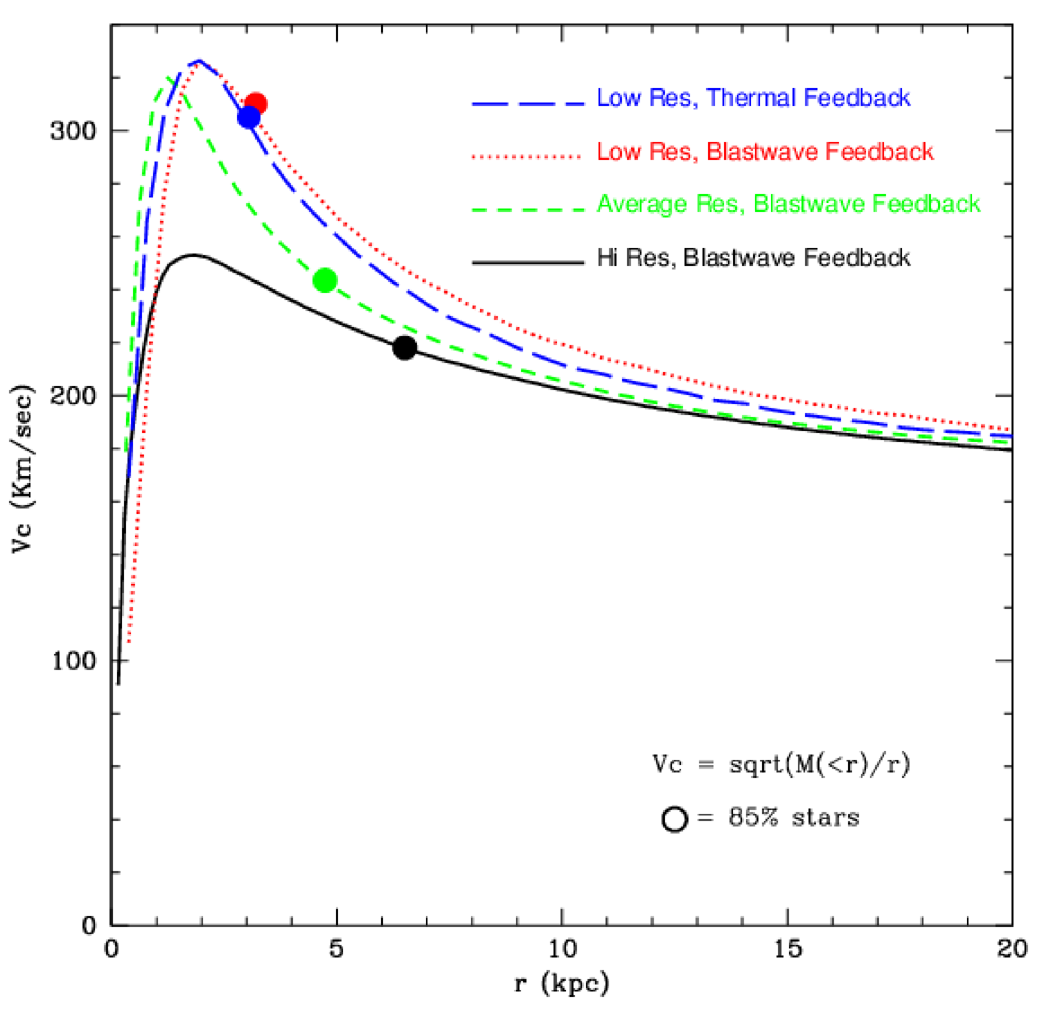


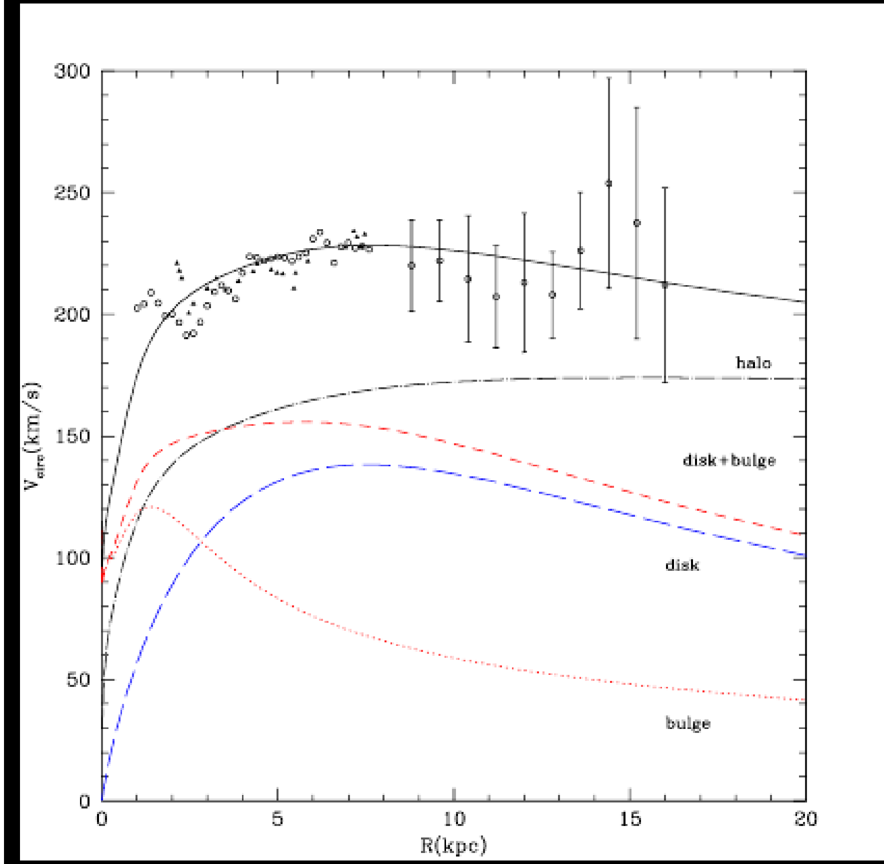

**Qualitative a** … **n et al. 2006 and Ho** … **ion as high as 50%** …

***--→ gas fract*** …

***~15-20% but 3x times more gas is in the smooth halo + cold flows attached to the two galaxies***

# Circular velocity profiles vs. resolution: *revisiting the mass concentration problem*



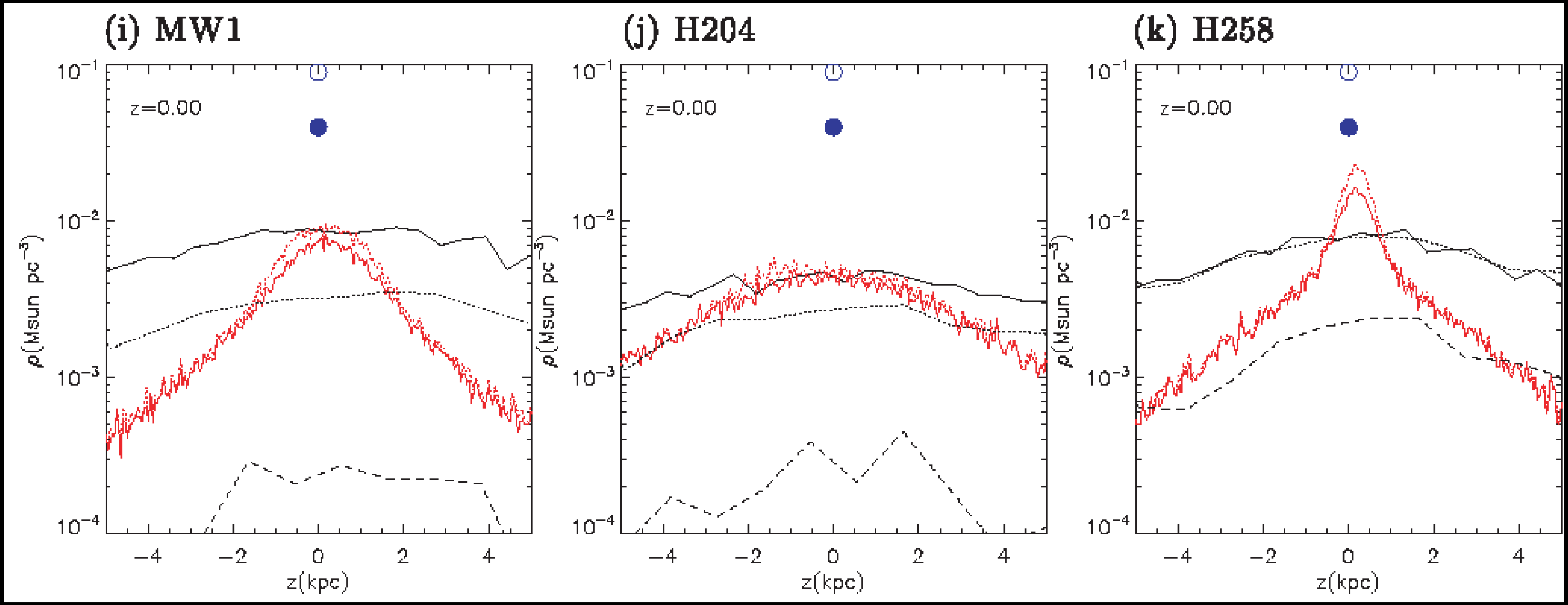




*Governato, Mayer, Brook 2008*
*Mayer, Governato & Kaufmann, 2008*

**At high resolution rotation curve begins to approach that of an early-type spiral galaxy --→ converge with increasing resolution?**
**What about flat (e.g. MW) or slowly rising rotation curves (e.g. dwarfs, LSBs)?**

**Mass distribution in simulated galaxies close to Sa galaxies (B/D ~ 0.5)**
**(Governato et al. 2009; Mayer, Governato & Kaufmann 2008)**
**--→ bulge is more massive and disk is less massive (~2-3 times) compared to Milky Way→ *stellar/baryonic surface density at the solar radius lower than that in the Milky Way* *(Read, Mayer et al. 2009)***

***All these simulated galaxies have stellar mass comparable to that of the Milky Way***

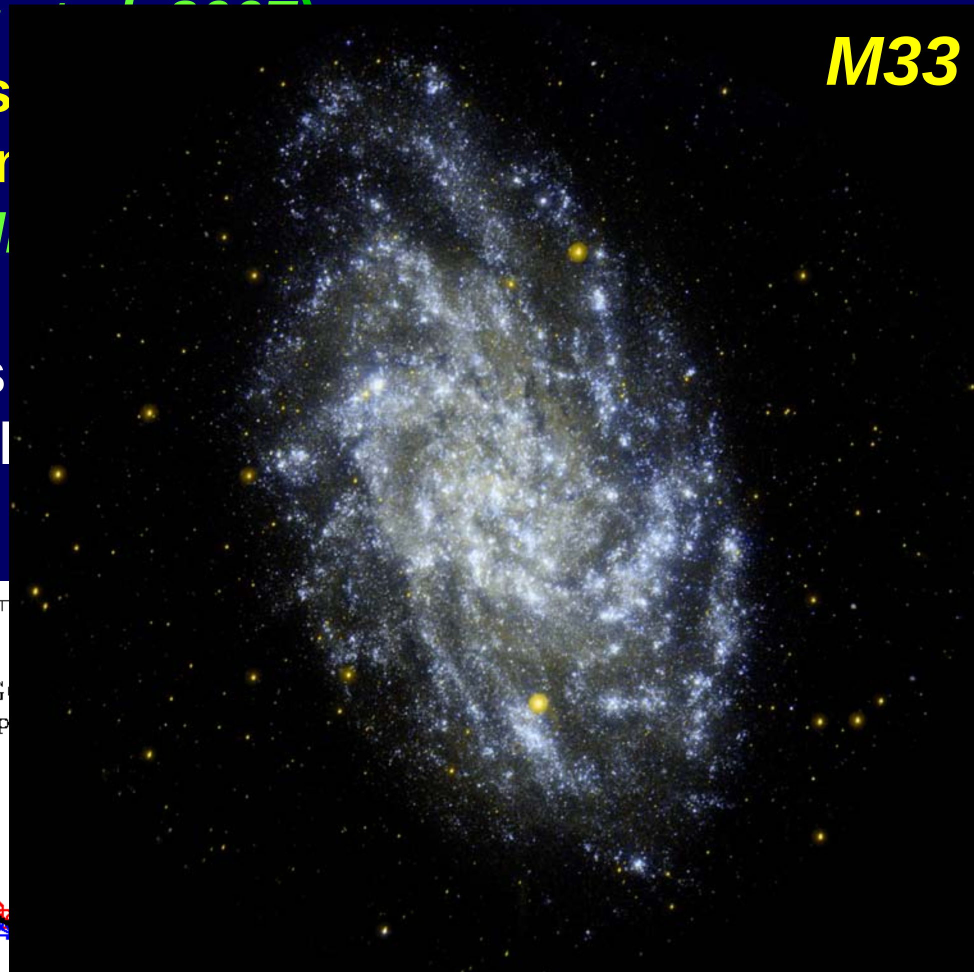


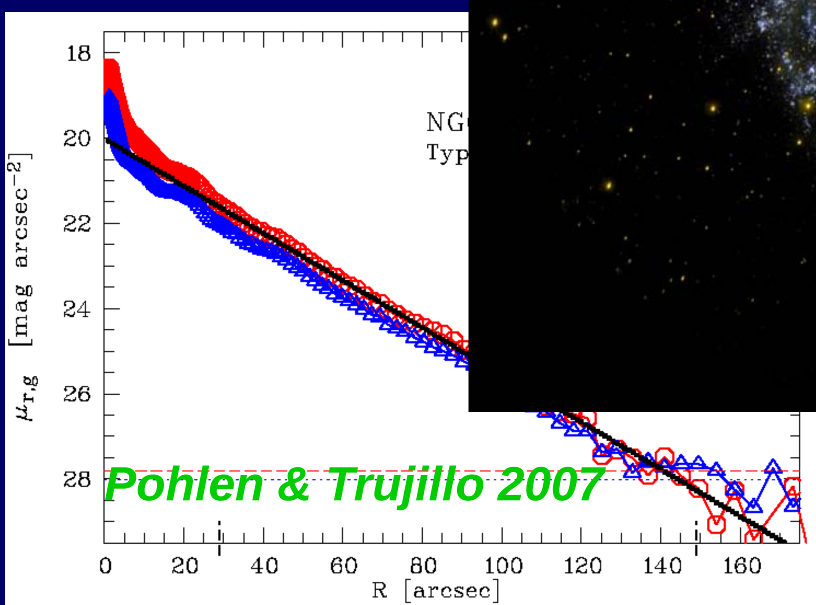

***MW Data (blue dots) from Holmberg & Flynn 2000***

➢*30% of disk galaxies are late-type, with little or no bulge, out to at 0 < z < 1 (e.g zCOSMOS survey results of* ***Sargent***

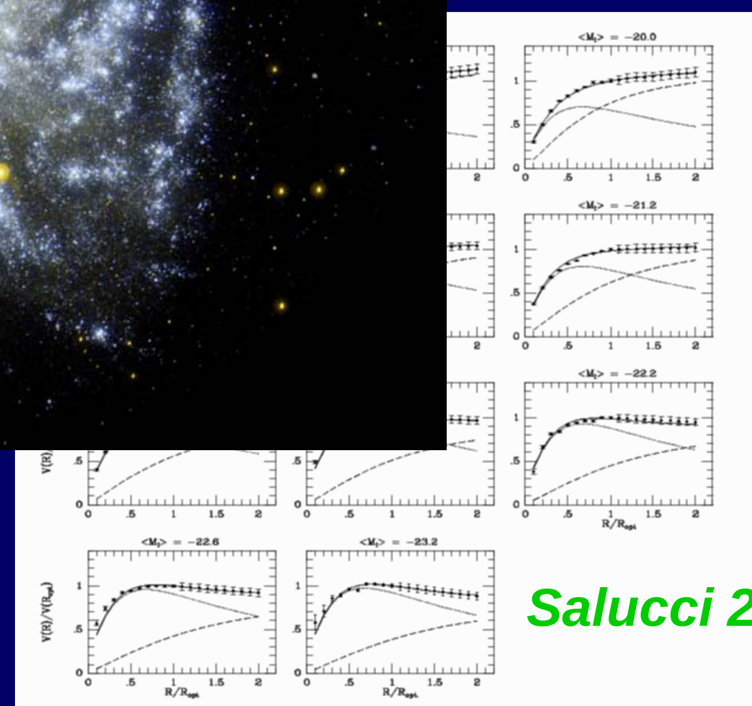
▪**Bulgeless** … **have slowly risi**… ***et al. 2008, THINGS H***… **ofiles**

▪**The mass** … **possible to form bul**… **s till 2009**




***Pohlen & Trujillo 2007***




***Salucci 2007***

# The star formation density threshold: tests with hi-res isolated galaxy models

***"Low" density threshold (corresponds to WNM - adopted in all cosmological simulations by all groups till 2009)***

$\rho > 0.1\ \mathrm{cm}^{-3}$

***"High" density threshold (corresponds to molecular gas), feasible only at hi-res***

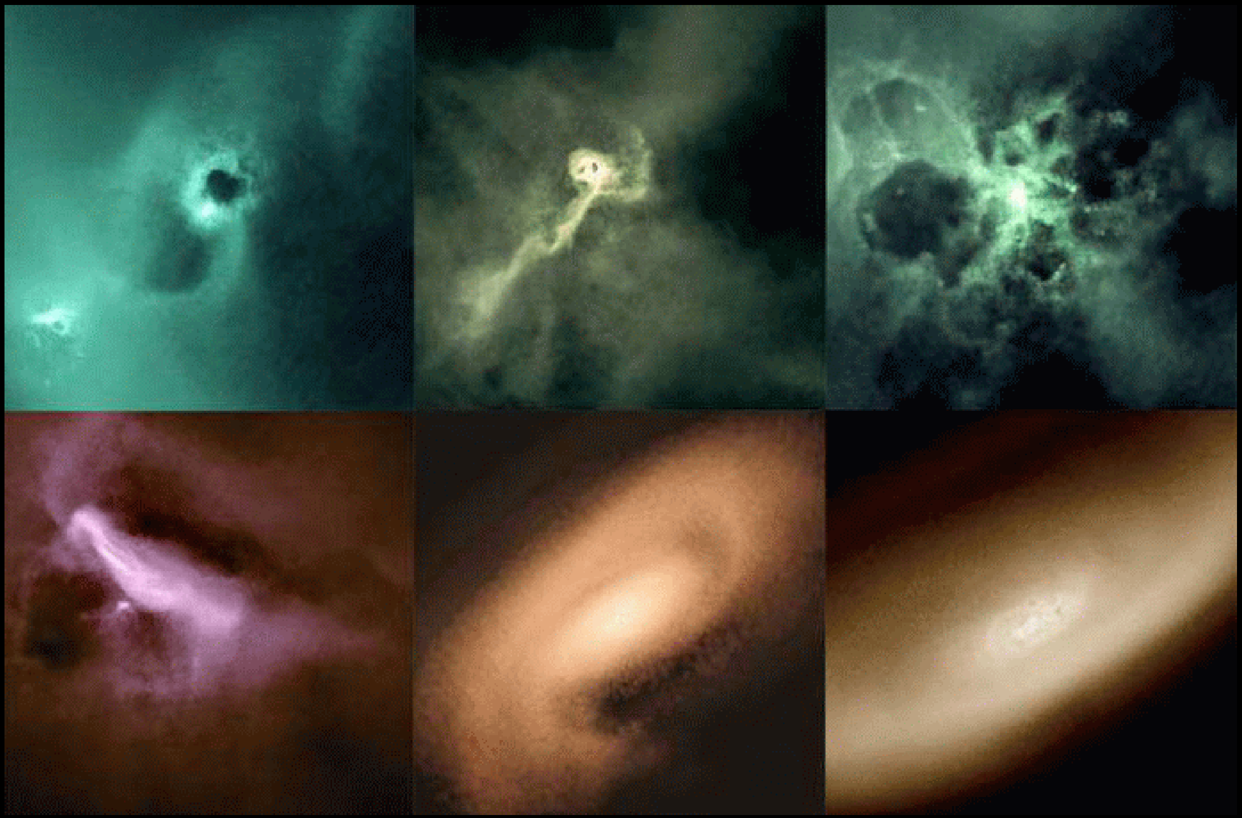
$\rho > 100\ \mathrm{cm}^{-3}$

***Callegari, Brook, Mayer, Governato, 2009***

***See also Robertson & Kravtsov 2008; Gnedin et al. 2009; Pelupessy et al. 2009***

# First hi-res dwarf galaxy formation simulation

$Vc_{halo}$ ~ 50 km/s
NSPH ~ 2 x $10^6$ particles
Ndm ~2 x $10^6$ particles
( Msph ~ $10^3$ Mo)
spatial resolution
(grav. softening) 75 pc
→Order of magnitude better than any cosmological hydro simulation taken to z=0



- High SF threshold
100 atoms/$cm^3$

-Supernovae blastwave feedback model with same parameters as in previous MW-sized galaxies simulations

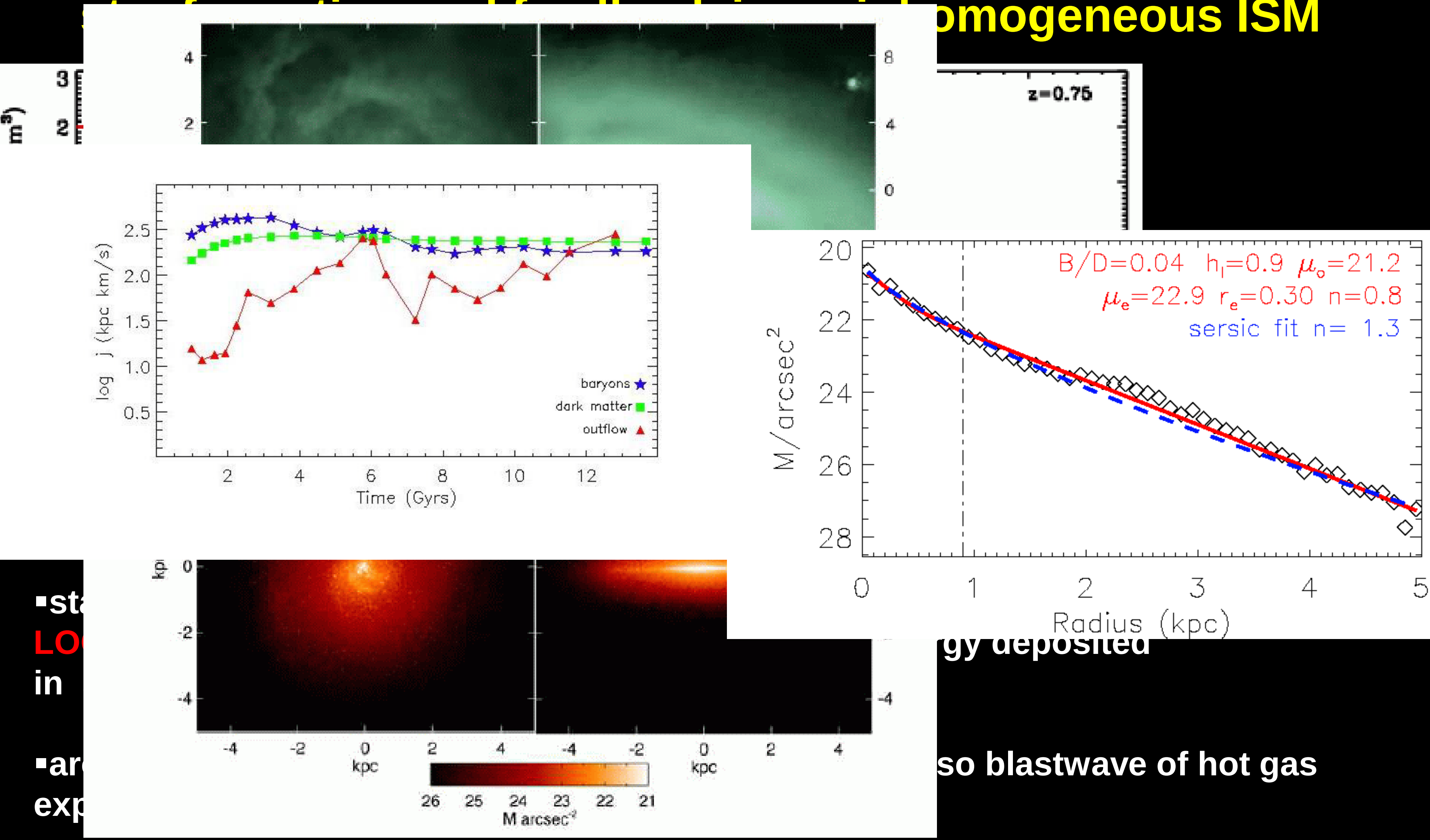
- Cooling function includes metal lines (gas cools below $10^4$ K)
+ heating by cosmic UV background (Haardt & Madau 1996 + 2006)

Governato, Brook, Mayer et al., Nature, Jan 14, 2010

+ News and Views article by M. Geha


0 Gyrs

# New solution of the mass concentration problem;
# ... omogeneous ISM

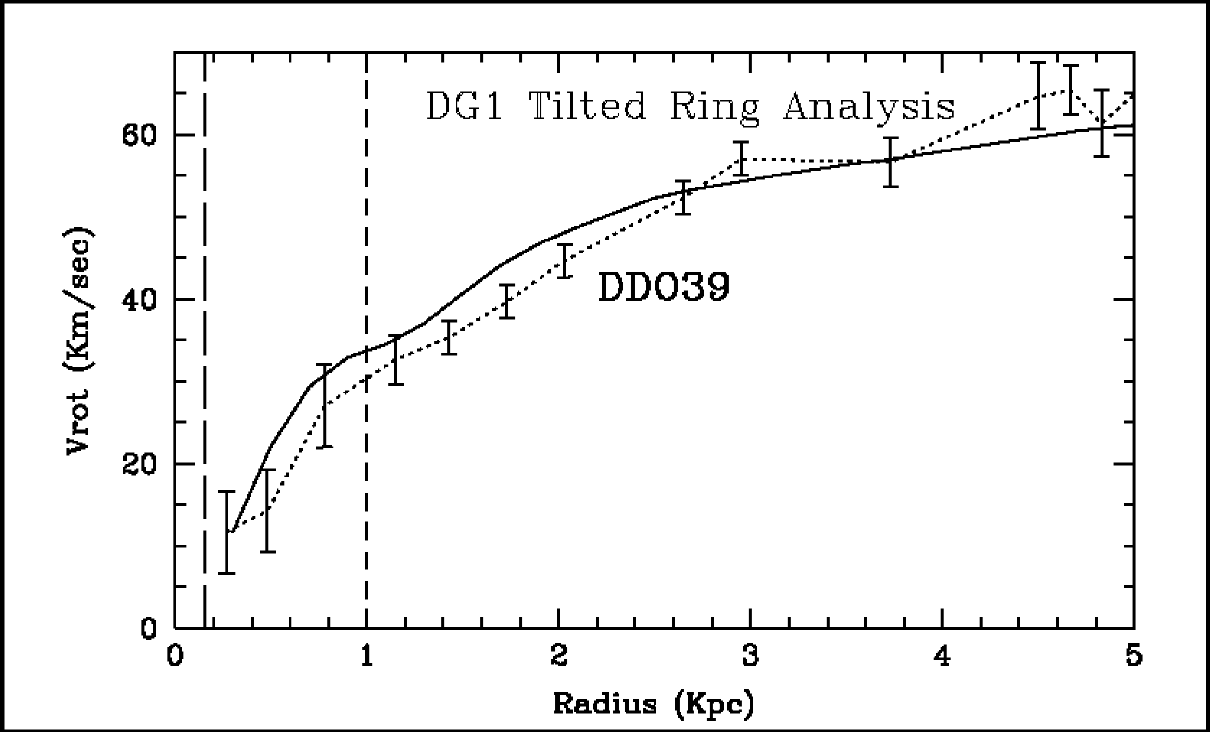



▪st ... LO ... gy deposited in

▪ar ... so blastwave of hot gas exp ...

▪Outflows mostly in the center of galaxy where density peaks higher -→ remove low angular momentum material from the center -→ *suppress bulge formation and produce exponential profile for stars*

## -→ *and produce a slowly rising rotation curve!*

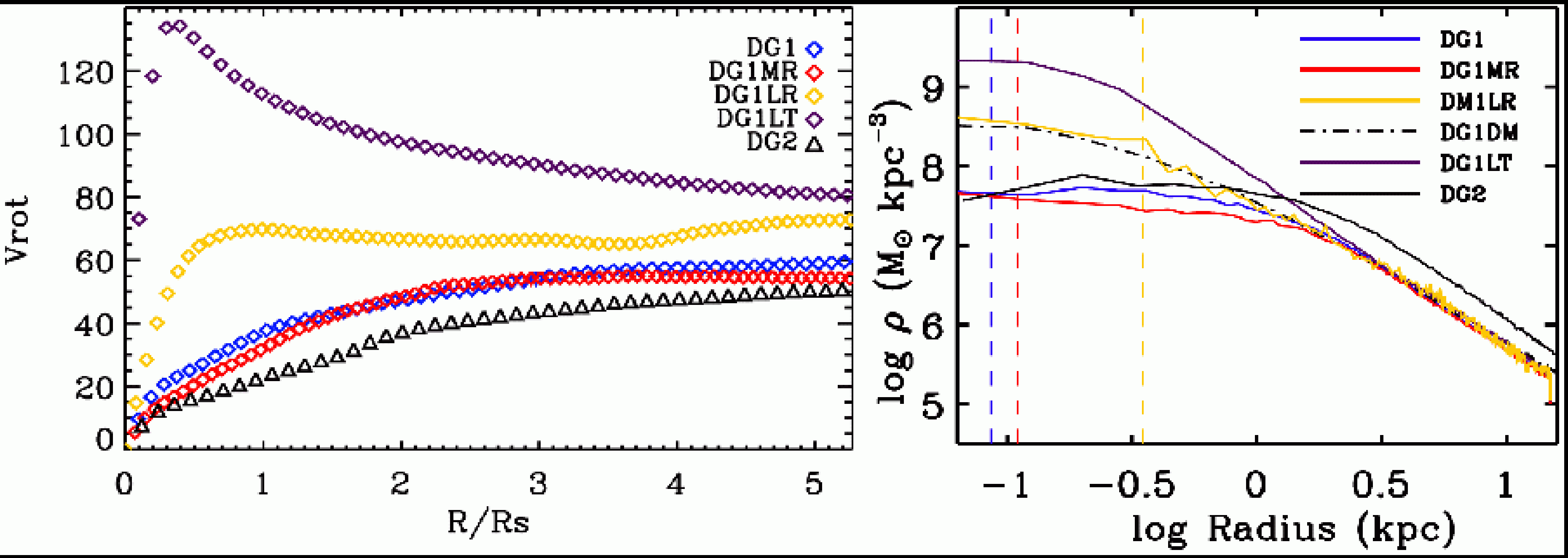



**How? Removal of baryons (baryonic disk mass fraction ~ 0.03 at z=0, so 5 times lower than cosmic fb) + flattening of dark matter profile**
**During strongest outflows (at z > 1) inner dark matter mass expands as a result of impulsive removal of mass**
***(confirms earlier toy models of e.g. Navarro et al. 1996; Read et al. 2003)***

***Dark matter density decreases by a factor of ~ 2 at r < 1 kpc and density profile becomes shallower ~ $r^{-0.6}$ rather than ~ $r^{-1}$***

# Enlightening numerical tests

"Erosion" of dark matter density cusp occurs only at high resolution and high star formation density threshold because it is only in such configuration that prominent baryonic mass outflows do occur



***And now let us switch to formation of massive galaxies (S0s, ellipticals)***

**If mergers (gas-rich) produce disk dominated galaxies what about early-type galaxies - S0s and ellipticals?**

***Can the “hi-res + blastwave feedback” recipe also produce massive early-type galaxies seen in groups and clusters?***

# HI-RES COSMOLOGICAL SIMULATIONS OF $10^{13}$ Mo groups

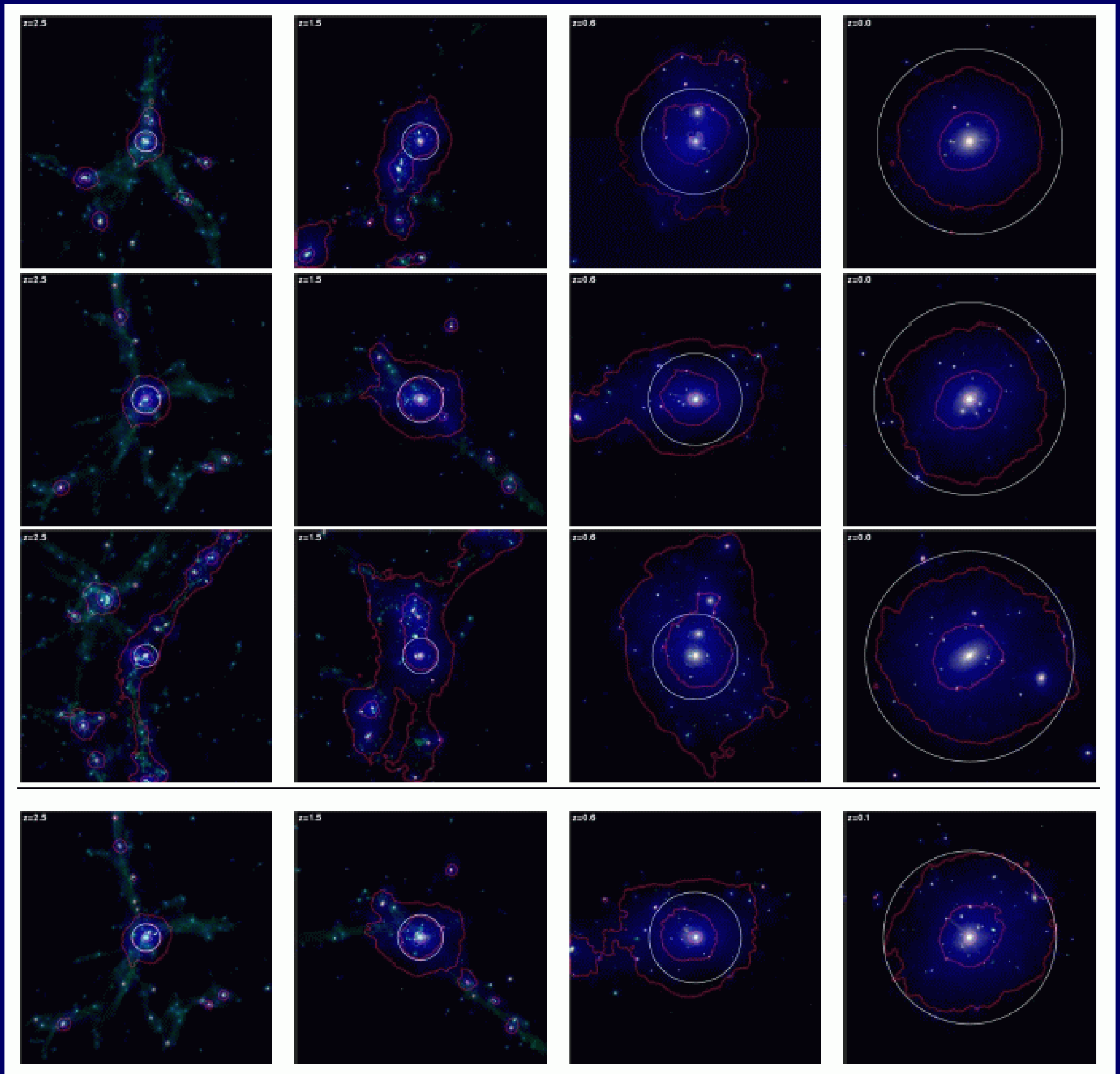
**3 groups with ~ same mass at z=0 but different assembly histories (e.g. frequency of major mergers) and different local environment at z=0**

***G1***

***G2***

***G3***

***G2-HR***



*Feldmann, Carollo, Mayer et al. 2009*

*+*

*Feldmann, Mayer et al, In prep.*

***BRI filterbands image***

# Central galaxies of 3 different groups at z=0

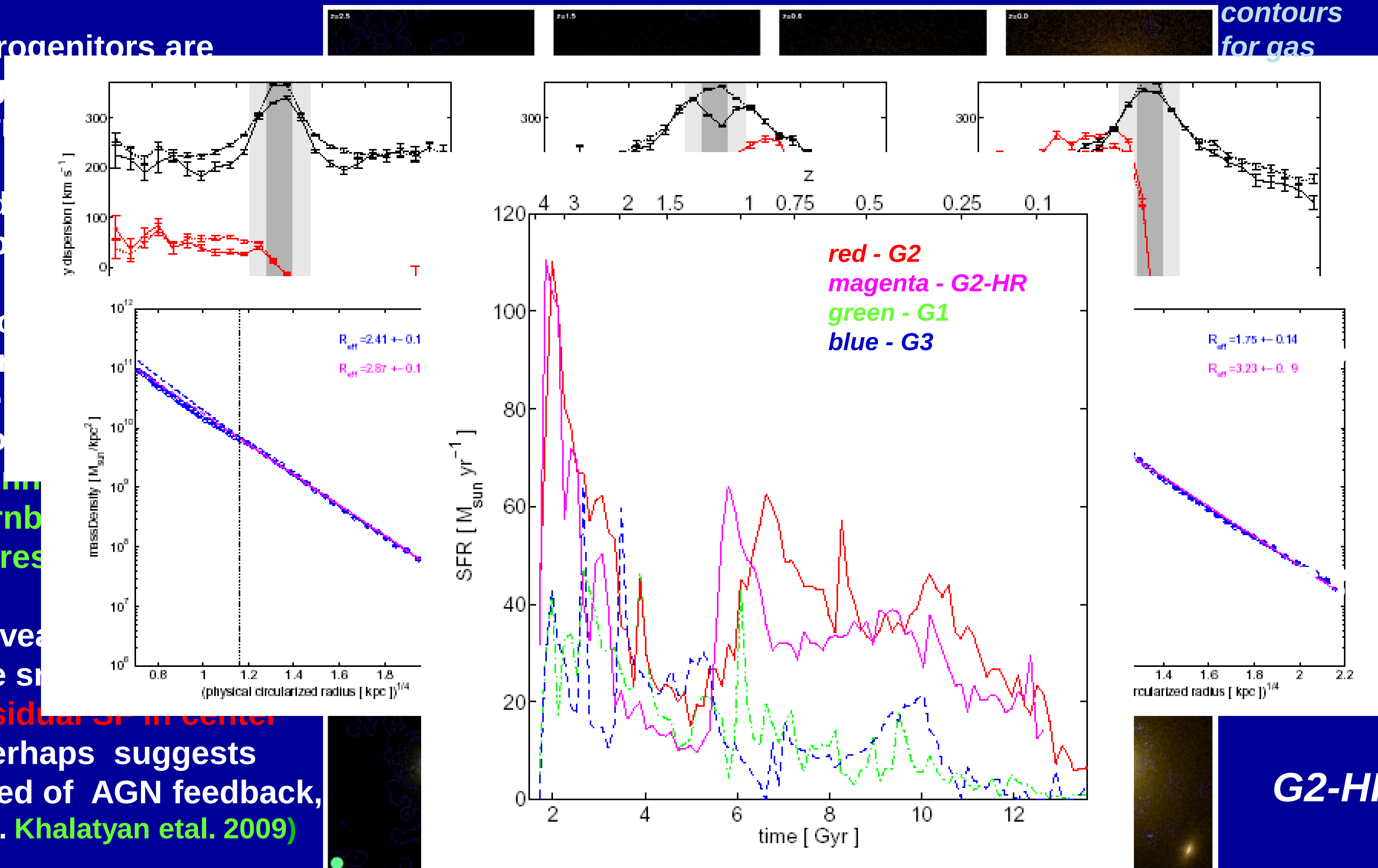
By z=0 morphology, colors, structure, kinematics of central galaxies consistent with massive S0 or ellipticals (B/D > 1.5, M* ~3-4 x $10^{11}$Mo)

*BRI stellar images + blue contours for gas*

▪Progenitors are
hig
for
at
red
(up

▪Co
do
z >
mo
(Bir
Birnb
Keres

Cavea
the sr
residual SF in center
(perhaps suggests need of AGN feedback, e.g. Khalatyan etal. 2009)

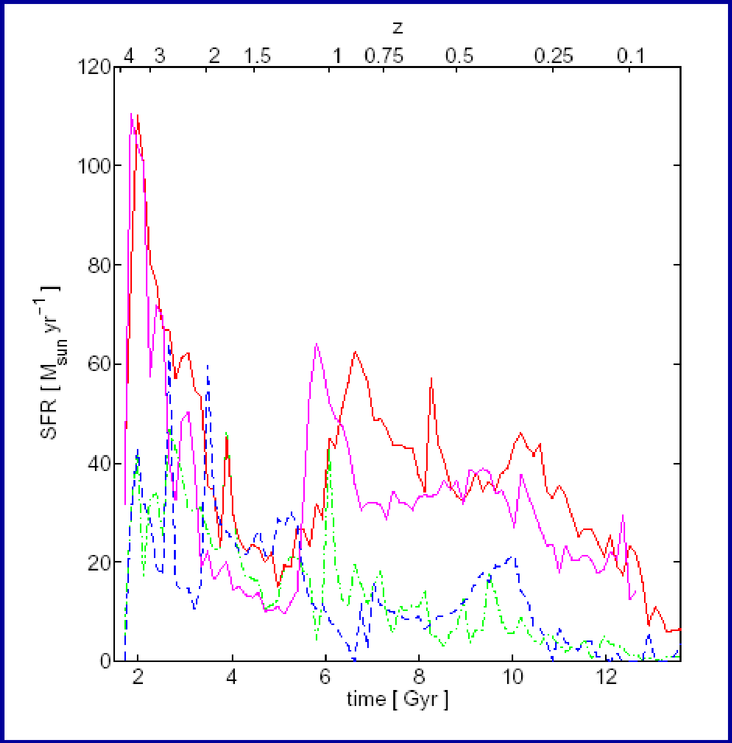


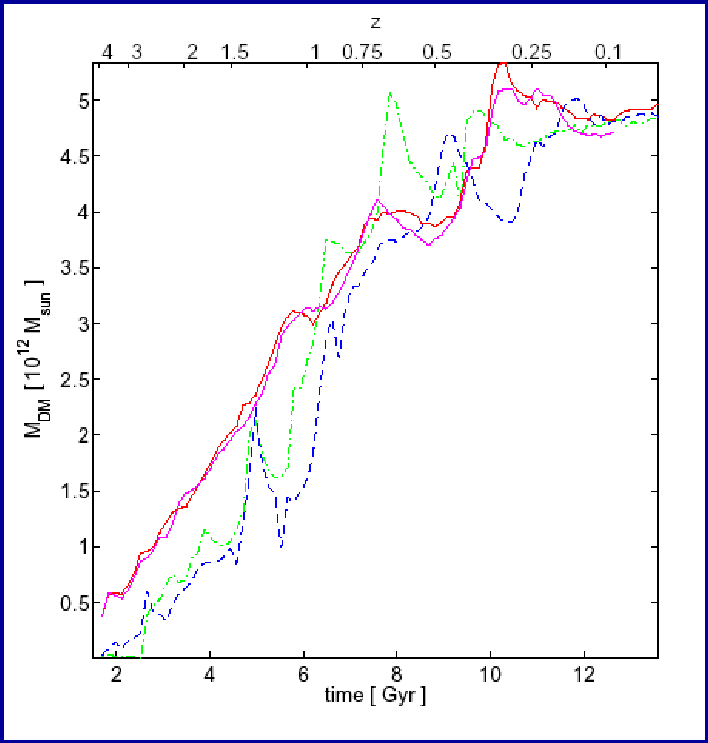

*G2-HR*

# Mergers at $10^{13}$ Mo scale - drive towards earlier type

- G2, the most quiescent group (last merger > 1:4 at z ~ 4), is the one with more prolonged star formation and more significant disk component at z=0 (classified S0)
- G1, builds 70% of its mass by repeated major mergers (last at z ~ 0.4) - is the one which matches better properties of a massive elliptical (no gas, no SF, red, boxy isophotes)

***At this mass scale objects become hot mode dominated already at z ~ 2-2.5 -→ major mergers do not bring cold gas but shock-heat the gas quenching cooling and SF + low-z "dry" mergers heat the disks into spheroids***




*Halo assembly history for G1, G2, G2-HR, G3*

**Residual star formation and excess baryonic density/small effective radii all suggest that additional heating source needed to quench cooling and star formation and form a “typical” early-type galaxy in CDM**

**Obvious candidate is feedback from central Active Galactic Nuclei (AGN) since supermassive black holes (SMBHs) ubiquitous in massive early galaxies (see e.g. review by Cattaneo et al. 2009)**

**Various sub-grid models for AGN feedback exist (e.g Springel et al. 2005; Sijiacki et al. 2007,2008) Booth & Schaye 2009) but none of them is based on a self-consistent physical model (hard multi-scale problem), neither it is clear how SMBHs form and how/when they become large enough to constitute a major player in the galactic energy budget (likely requires $M_{BH} > 10^6$ Mo)**

**---→ *SMBH formation problem***

At z > 6 bright QSOs already exist *(Fan et al. 2003; Fan 2006)*

**Assuming Eddington-limited accretion QSOs luminosities ($> 10^{47}$ erg/s) yield $M_{BH}$ >~ $10^9$ Mo.**

**Conventional SMBH formation model** (e.g. Madau & Rees 2001; Volonteri et al. 2003) *– Pop III stars formed at z ~ 20-30 form first massive seed BHs ($M_{BH}$ ~ 100 Mo) that then grow via gas accretion (and partially via mergers wih other SMBHs)*

**Question: Can a $10^9$ Mo SMBH gowr ~ 100 Mo Pop III seed in less than 1 Gyr (time elapsed up to from z=20-30 to z=6)?**

**Answer:** *For realistic radiation efficiencies ($\varepsilon$> 0.1) would need to accrete >~ Eddington starting from ~ 100 Mo seed*

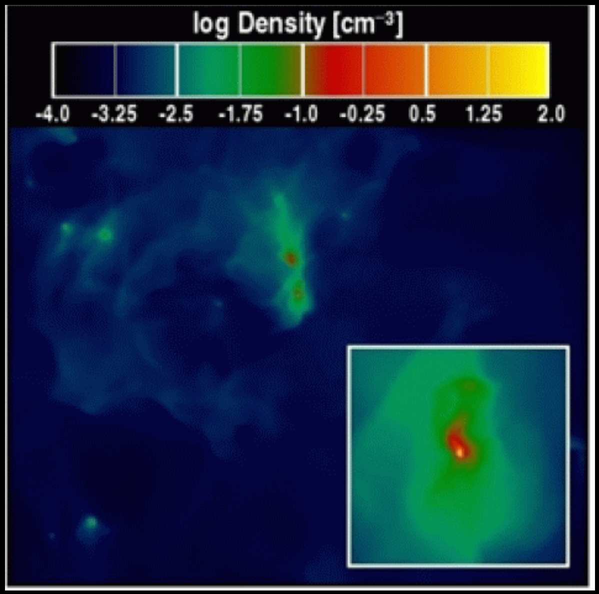
(Volonteri & Rees 2006)

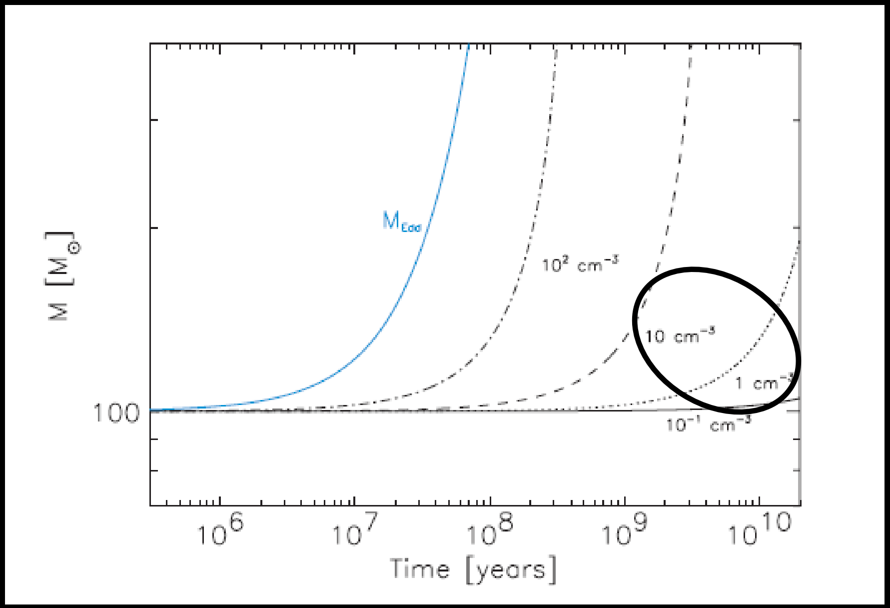
$$M(t) = M(0)\,\exp\left(\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\rm Edd}}\right)$$

*Shapiro 2004*

$t_{edd}$ ~ 0.45 Gyr

# Growth from Pop III seed BHs: quite inefficient

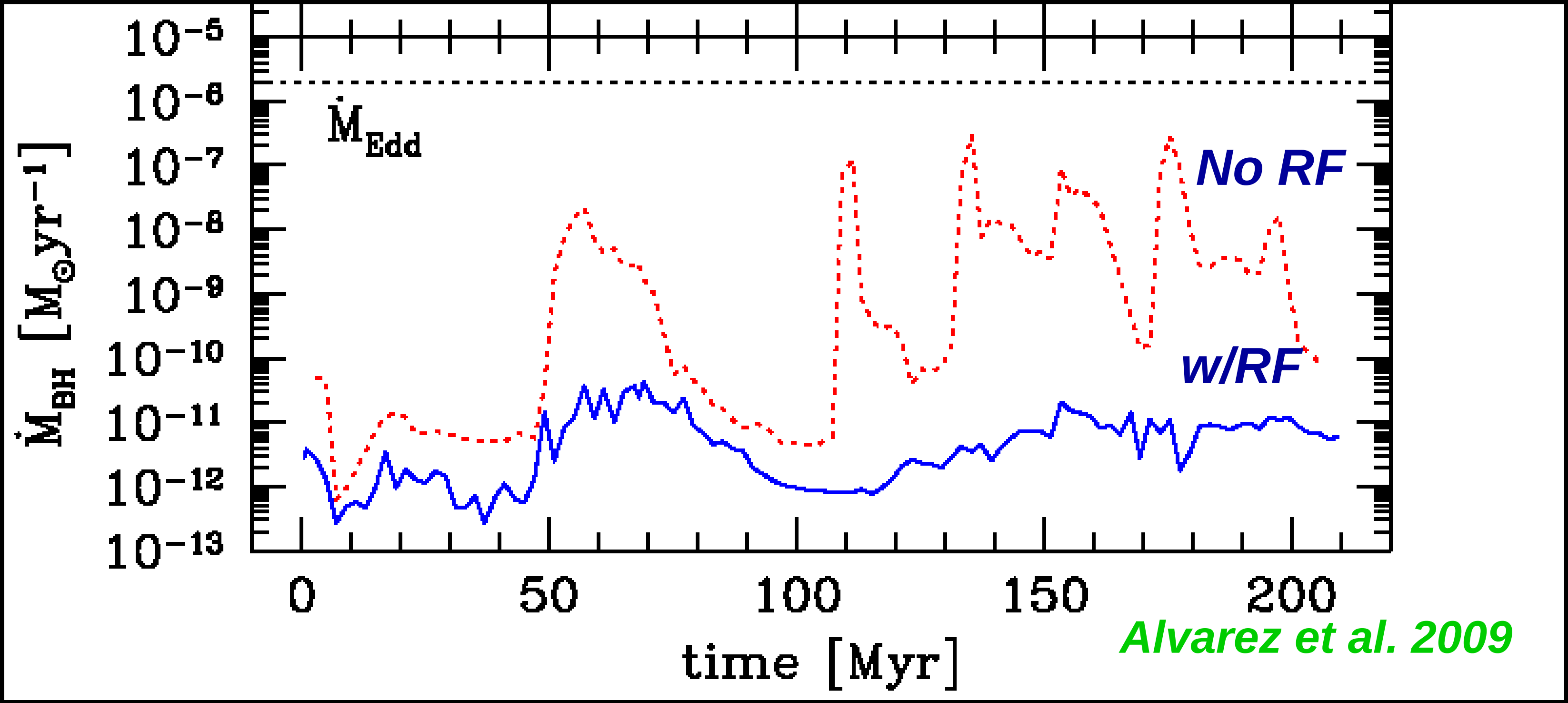



*Johnson & Bromm 2007*

**- Pop III star creates HII region with low density gas (~< 1 $cm^{-3}$) -→** ***Accretion very sub-Eddington for almost 1 Gyr until gas cools and recombines*** **(mergers of pristine, non-ionized minihalos included, but NO radiative feedback from accretion)**

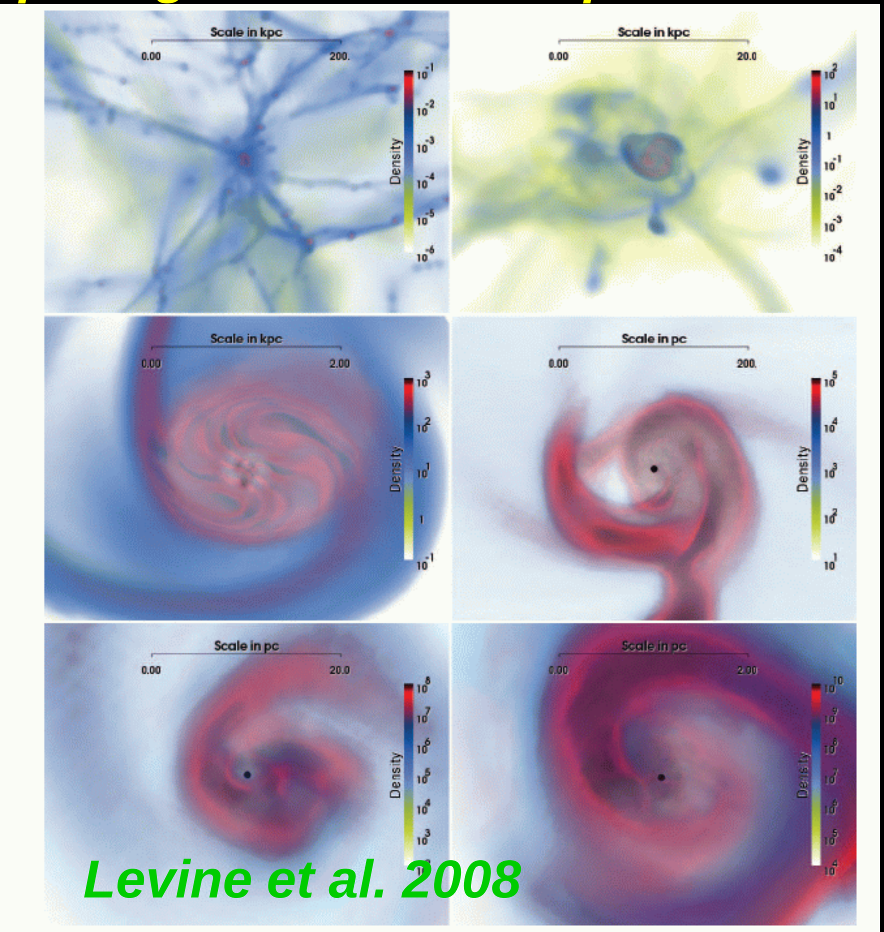
**-Inefficient growth (0.1-0.2 Eddington) found also in simulations that have lower resolution but are fully cosmological**
**--→ *$M_{BH}$ ~$10^5$-$10^6$ Mo after 1-2 billion years* (Pelupessy et al. 2007)**

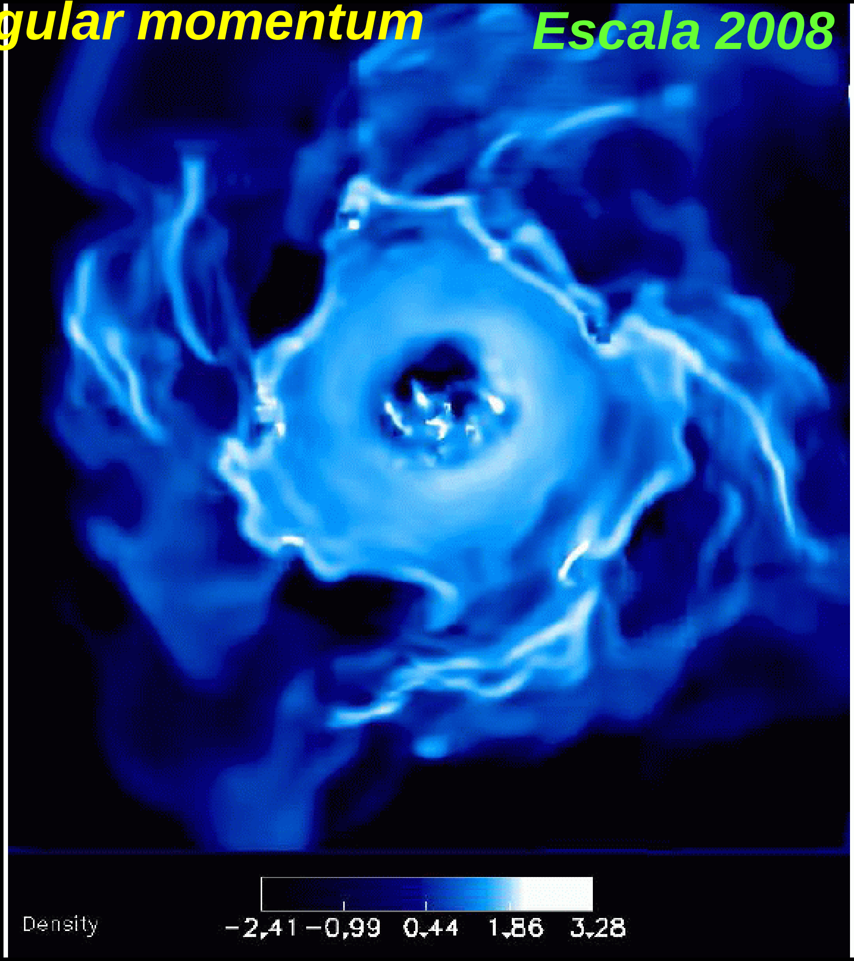



- *Radiative feedback from accretion onto see BH lowers density further (Alvarez et al. 2009)*
- *Radiation pressure stifles accretion further (Milosavljevic et al. 2007;2008)*

Alternative: direct formation of SMBH seed ($M > 10^5$ Mo) via runaway gas collapse (e.g. Begelman et al. 2006; Shapiro et al. 2004)

Step I – triggering global gravitational instabilities in protogalactic disks to produce loss of angular momentum




Step II - the bottleneck of star formation - as gas loses J and density grows Toomre stability parameter drops to Q < 1 ---→ rapid fragmentation into star forming clouds

# Multi-scale SPH gas-rich merger simulations of two galaxies ($M_{disk}$ ~ 6 x $10^{10}$ Mo) in $10^{12}$ Mo halos – resolution 0.1 pc in 10 kpc volume

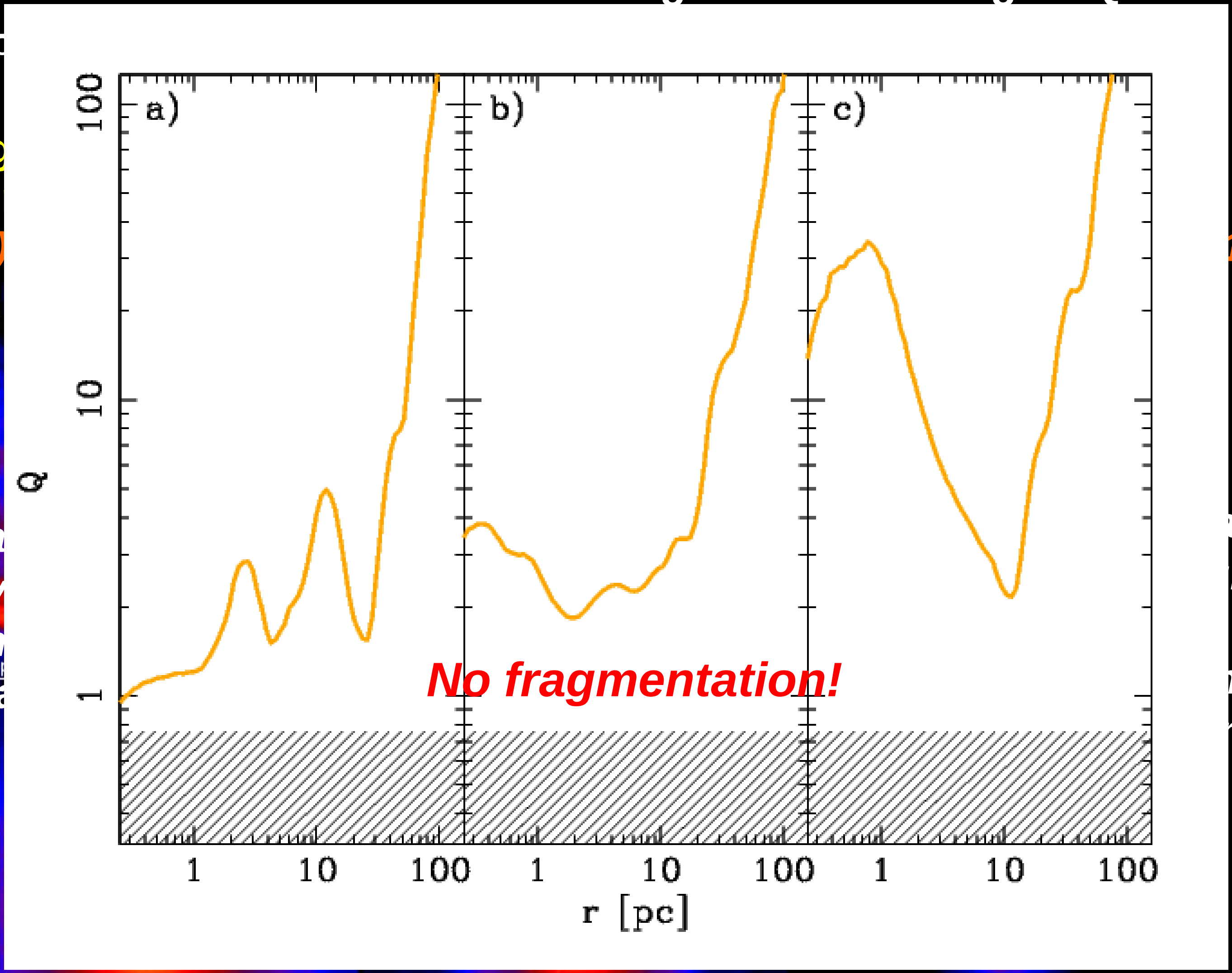
**Host halo mass consistent with clustering statistics of high z QSOs (rare 3-4σ**

**Multi-stag** … **forming in major me** …

*(> $10^8$ Mo)* … *$10^7$ yr)*

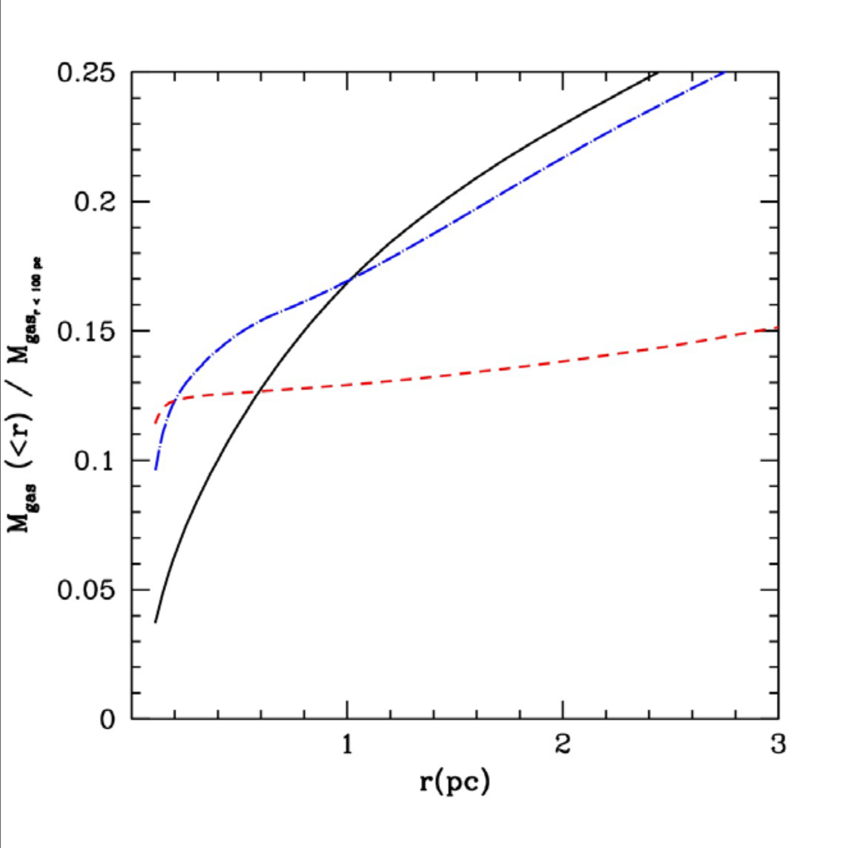
*Large sca… instability… pushes m… via gravita…*

*…l region …ndergoes … collapse …ation of …massive*




*No fragmentation!*

*Mayer, Kazantzidis, Escala & Callegari 2009*




*In the first $10^5$ yr we have:*

*Mass inflow rates*
*~$10^4$-$10^5$ Mo/yr*

*Expected star formation rate*
*(~0.1 x $M_{cg}/T_{orb}$)*
*~ $10^3$ Mo/yr*

*--→ inflow faster than*
*star formation*

▪**Cloud likely precursor of SMBH – at resolution limit cloud as massive as dense as quasi-star described in** ***(Begelman 2007; Begelman et al. 2006)***
**Supercloud still Jeans unstable at the resolution limit** – ***runaway collapse should continue (catastrophic neutrino cooling in hot core in Begelman et al. 2007)***

▪ **Rapid direct formation of ~$10^5$ Mo BH from < 1 % cloud mass**
***If forming at z ~ 7-8 through merger then can grow at 0.8-1 Eddington rate to $10^9$ Mo in < 3 x $10^8$ yr (no low-density gas as in HII region around Pop III seed)***

# Conclusions

**With hi-res + better sub-grid models no need to change cosmology!**

**(1) Massive early-type spiral galaxies (Sa) with realistic sizes obtained in ΛCDM simulations through a combination of high resolution (no spurious angular momentum loss) and blastwave sup. feedback**
***Unrealistically small disks disappear with more than $10^6$ resolution elements***
**However we still miss a good analog of the MW – need to reduce B/D further**

**(2) With ~ $10^3$ Mo res. in low-mass galaxies SF tied to regions with GMCs densities**
**Star formation becomes more clustered and blastwaves stronger locally**
**--→ *dwarf galaxy with slowly rising rotation curve and no bulge obtained.***
**At least in the two simulations performed the long standing "Cold Dark Matter Catastrophe" solved, no need of alternative DM models or alternative gravity (e.g. MOND). At higher mass scales perhaps B/D reduced to finally match MW?**

**(3) In $10^{13}$ Mo hi-res groups-sized halos we form central galaxies with properties akin to massive ellipticals and S0s, but need to increase effective radii by a factor of > ~ 2 and suppress residual SF -→ *points to important role of AGN feedback***
**(4) Modeling AGN feedback requires understanding of how SMBHs form and evolve during galaxy assembly.**

- **Slow growth from light Pop III seeds unlikely, direct collapse viable alternative**
- **First simulation of SMBH precursor forming in a gas-rich galaxy merger**