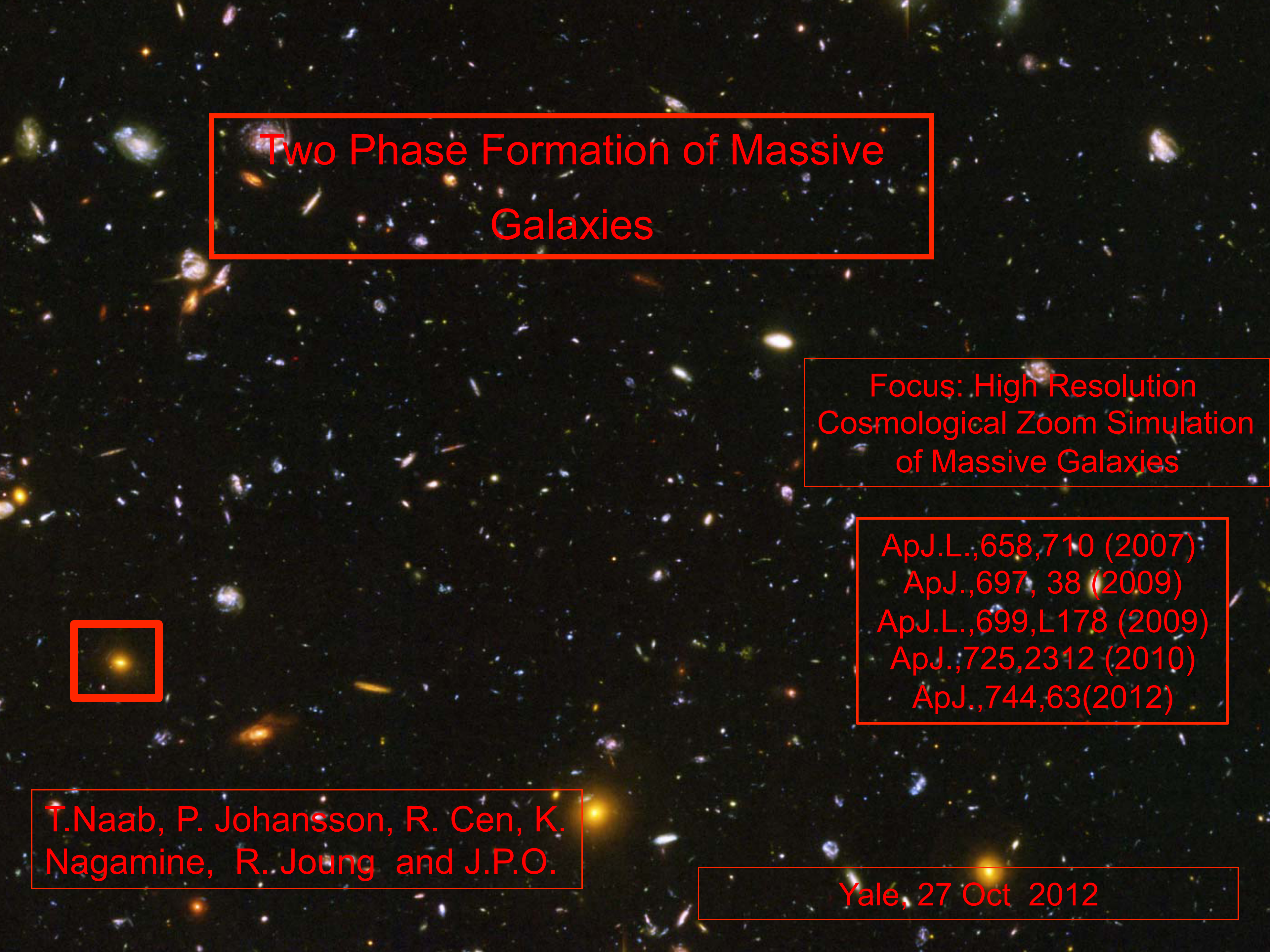

Two Phase Formation of Massive Galaxies

Focus: High Resolution Cosmological Zoom Simulation of Massive Galaxies

ApJ.L.,658,710 (2007)
ApJ.,697, 38 (2009)
ApJ.L.,699,L178 (2009)
ApJ.,725,2312 (2010)
ApJ.,744,63(2012)

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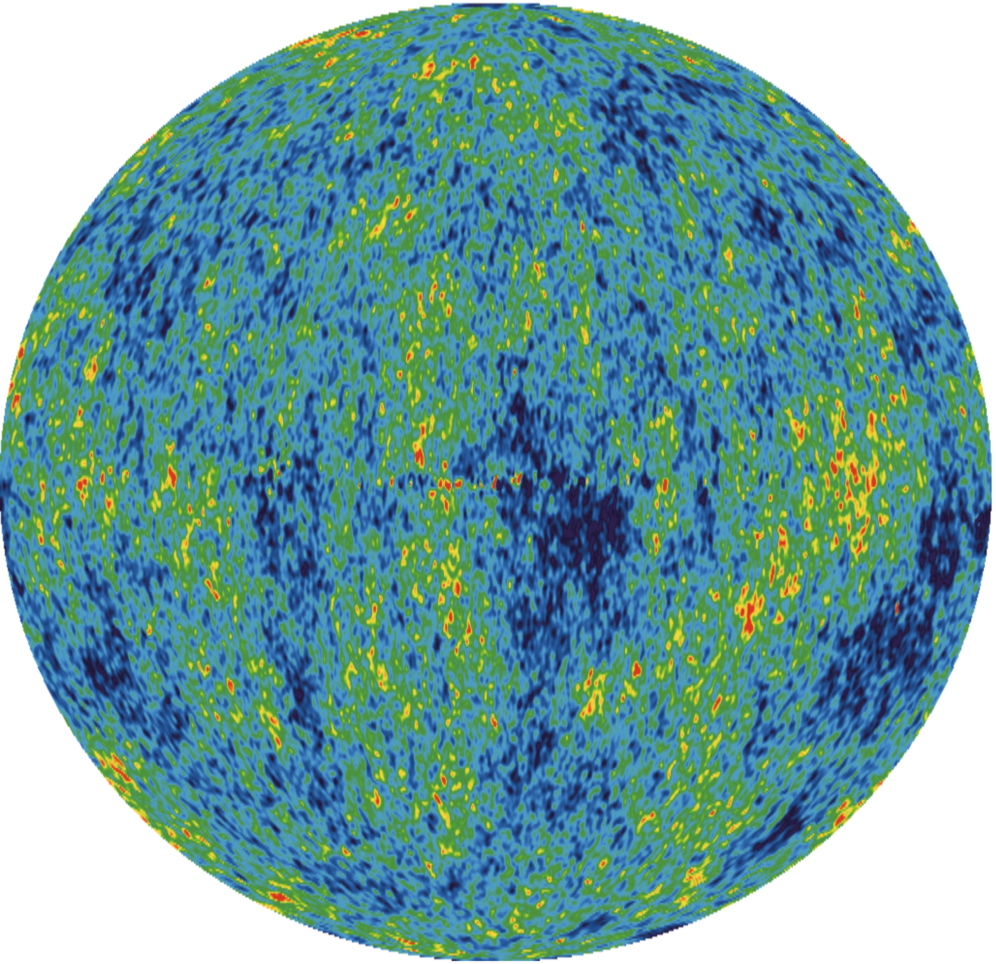
Yale, 27 Oct 2012

But first, what have we learned from 50 years of *observations*?

- Giant elliptical galaxies form early and grow in size and mass without much late star-formation.
- Major mergers are real but rare at late times (or else disk galaxies would have been destroyed).
- Dark matter does not dominate the inner parts of elliptical galaxies.
- Half of all metals are ejected from massive systems (*cf* winds and cluster metals).

NB, fluctuation level only 10^{-5} at high redshift

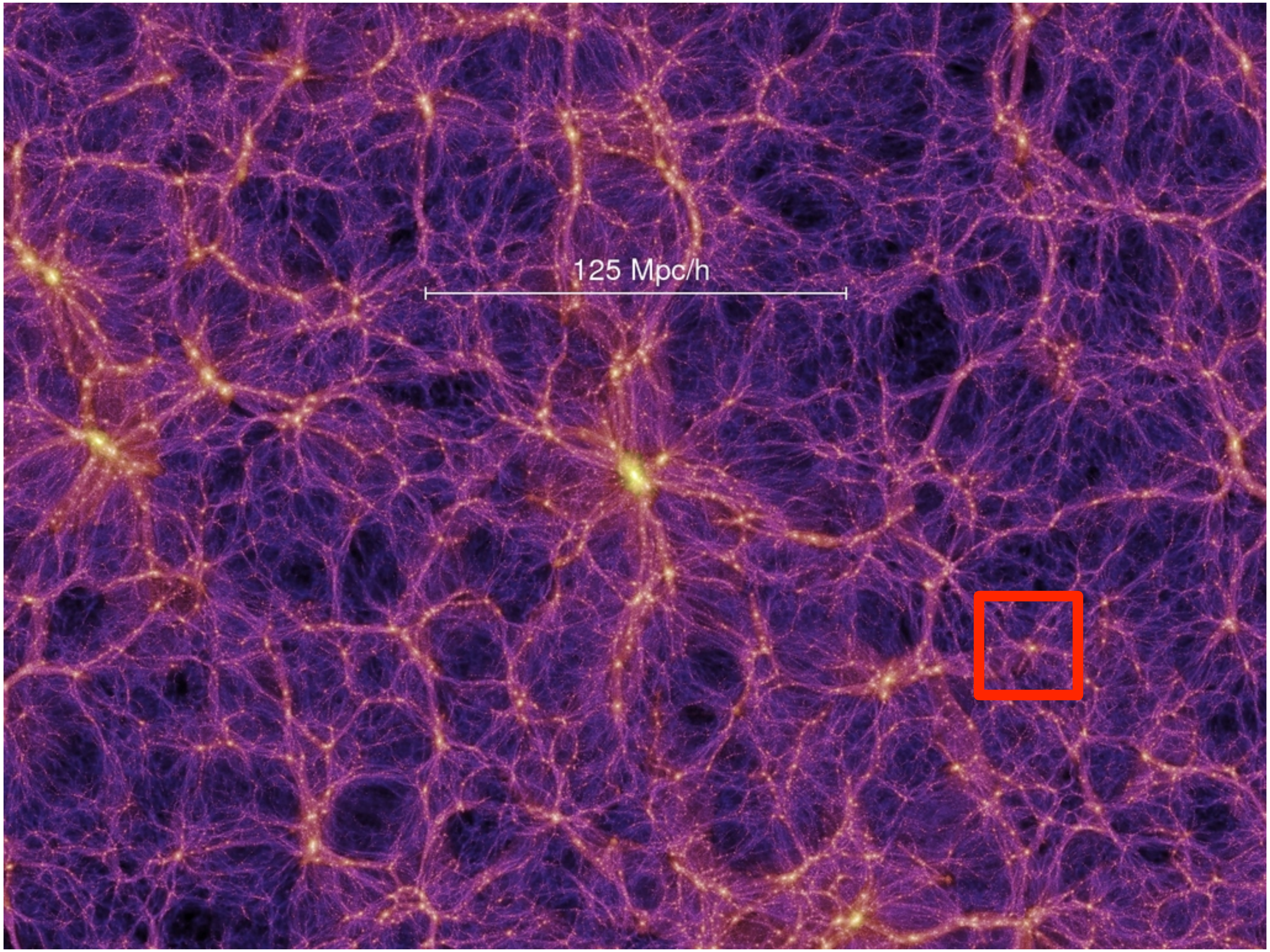
Cosmological Simulation: Start with WMAP CBR Sky



- Ω_{tot} = 1, [=1.010 +-0.016]
- Ω_{cdm} = 0.23 ± 0.01
- Ω_{baryon} = 0.046 ± 0.002
- Ω_{lambda} = 0.73 ± 0.02
- n = 0.963 ± 0.015
- H_0 = 70.4 ± 1.3km/s/Mpc
- σ_8 = 0.81 ± 0.02
- τ_{scat} =0.087 ± 0.001

(WMAP 7)

fast forward to structure growth computed in dark matter component ->



Second Step: hydrodynamic "Zoom Method" .

- Select region of interest.
- Put down finer grid.
- Add hydrodynamic equations.
- Add atomic physics: adiabatic, + cooling, +heating, + non-equilibrium ionization.
- Radiative transfer: global average, +shielding of sinks, +distribution of sources.
- Heuristic treatment of star-formation.
- Repeat calculation using tidal forces from larger region and do details of smaller region.

Star Formaton Algorithm

- Heuristic treatment of star-formation
  - For gas that is dense, cooling and collapsing make stellar particle:

    dM* = ***const*** x DMgas x dt/Max(Tcool,Tdyn).

    (***const ~ 0.025***)
  - Label particle with position, mass, metallicity and epoch.
  - Give particle velocity of gas and follow dynamics as if it were a dark matter particle.
  - Allow output of mass, energy and radiation from each particle consistent with a star-cluster of same mass and age – via standard stellar evolution theory: supernova

What have we learned?

- The onset of massive galaxy formation is early and follows re-ionization at $z = 6$.

High sigma peaks rapidly form stars from merging streams to initiate formation of cores of most galaxies. Disks and massive envelopes are formed later.

Overall Picture of Two-Phase Growth

Phase	In situ star formation	Accretion of stars
Epoch	6>z>2	3>z>0
Baryonic mass source	Cold gas inflows	Minor and major mergers
Size of region	< ~ 1kpc	~ 10 kpc
Stellar metallicity	Super-solar	Sub-solar
Energetics	***Dissipational***	***Conservative***

What is the observational* evidence (M. Kriek; '09)

z ~ 2.5

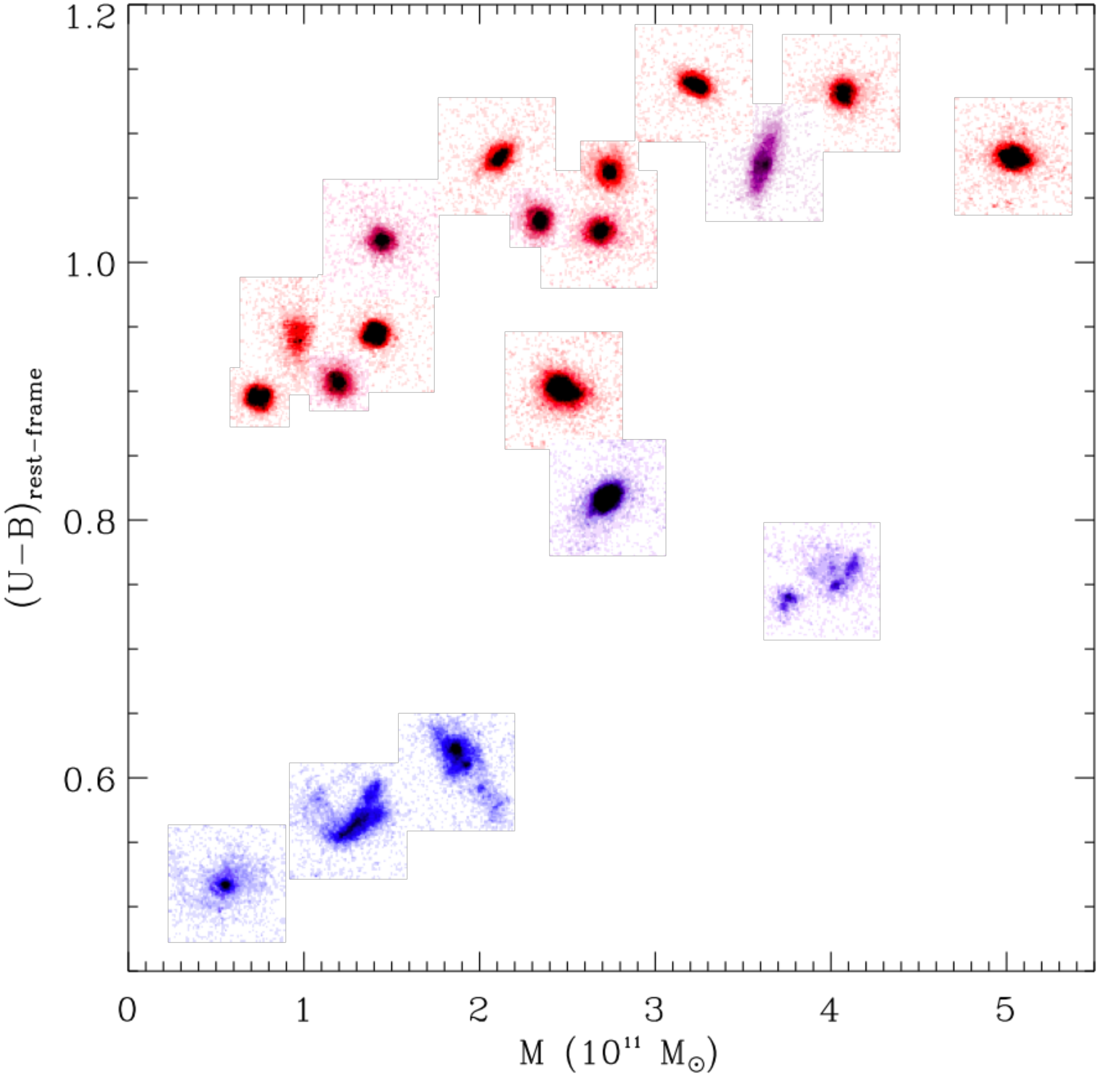
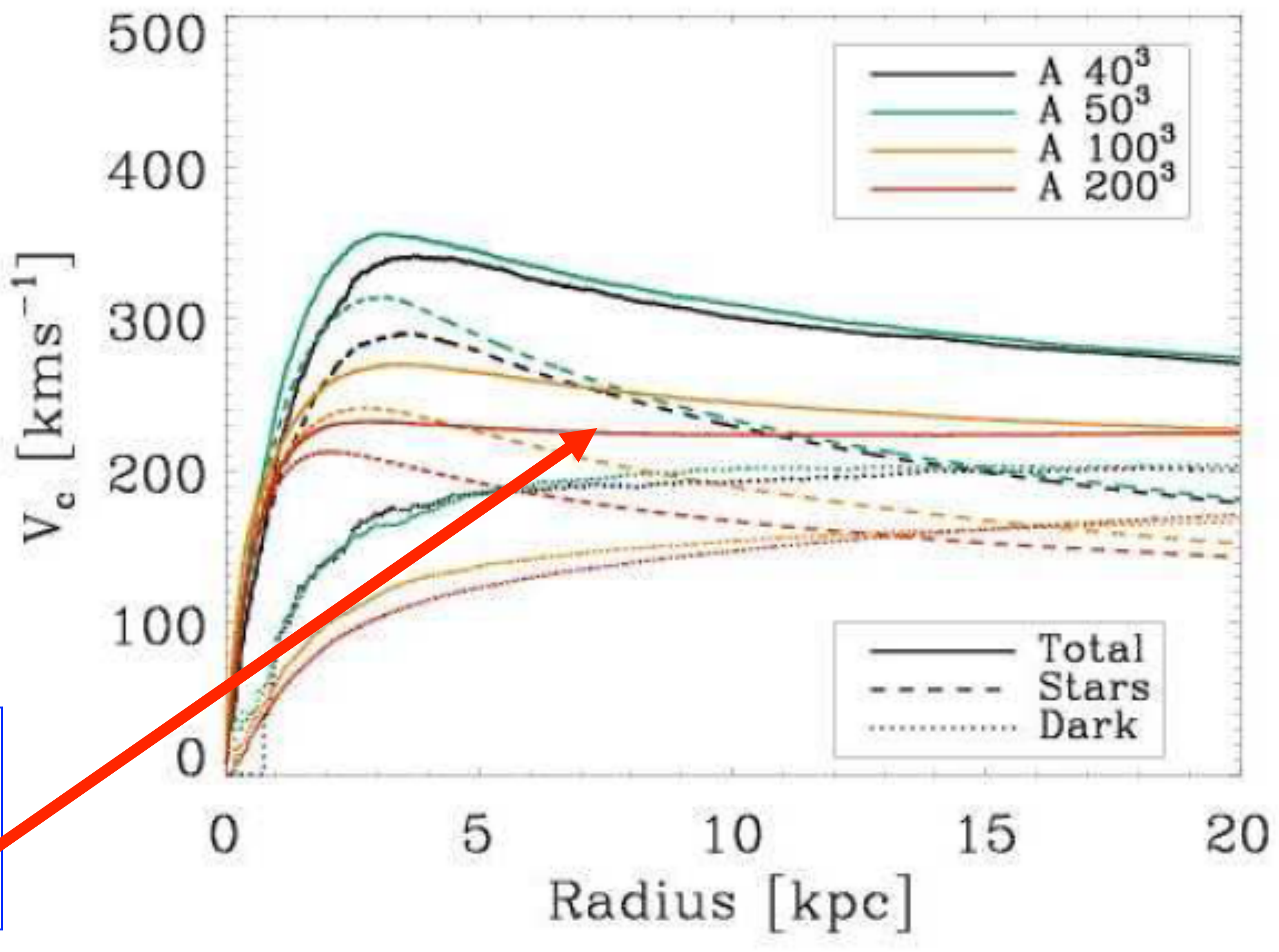


*Chart color represents specific star formation rate: high rate = blue.

Detailed Hydro Simulations (N,J,O&E : 2007, ApJ, 658,710)



Convergence to low and to a flat rotation curve at high resolution:

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.

In Situ Star Formation

Convergence to stellar system formed very early which quickly becomes “red and dead”.

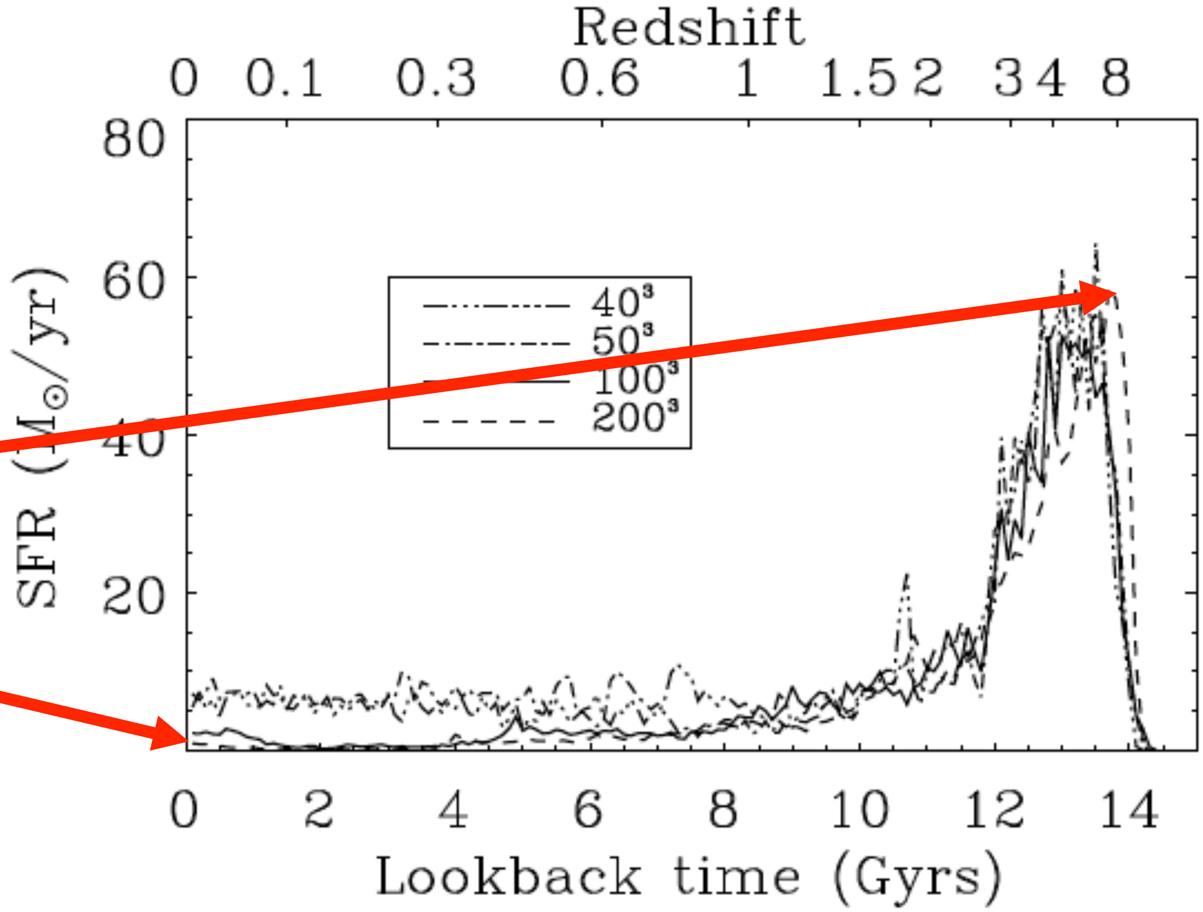


FIG. 2.— Star formation rate (SFR) histories, computed from stellar ages, of galaxy A versus lookback time at four different numerical resolutions: 40^3, 50^3, 100^3, and 200^3 SPH particles and collisionless dark matter particles, respectively. There is a strong trend that the low redshift star formation rate is reduced in higher resolution simulations.

Questions

- 1) Convergence: how do results change with resolution improvement; and why was high resolution needed?
- 2) Why does gas temperature increase though cooling time is short and no feedback was included?
- 3) Why is there a dramatic evolution of size?
- 4) Why is galaxy “red and dead” early but continues to grow in luminosity?
- ***ANSWER: TWO PHASE GROWTH WITH LARGE GRAVITATIONAL HEATING IN THE SECOND PHASE.***

Gas Properties

Gas, at all radii, becomes hotter with time despite fact that the “cooling time”< the Hubble time! Why?

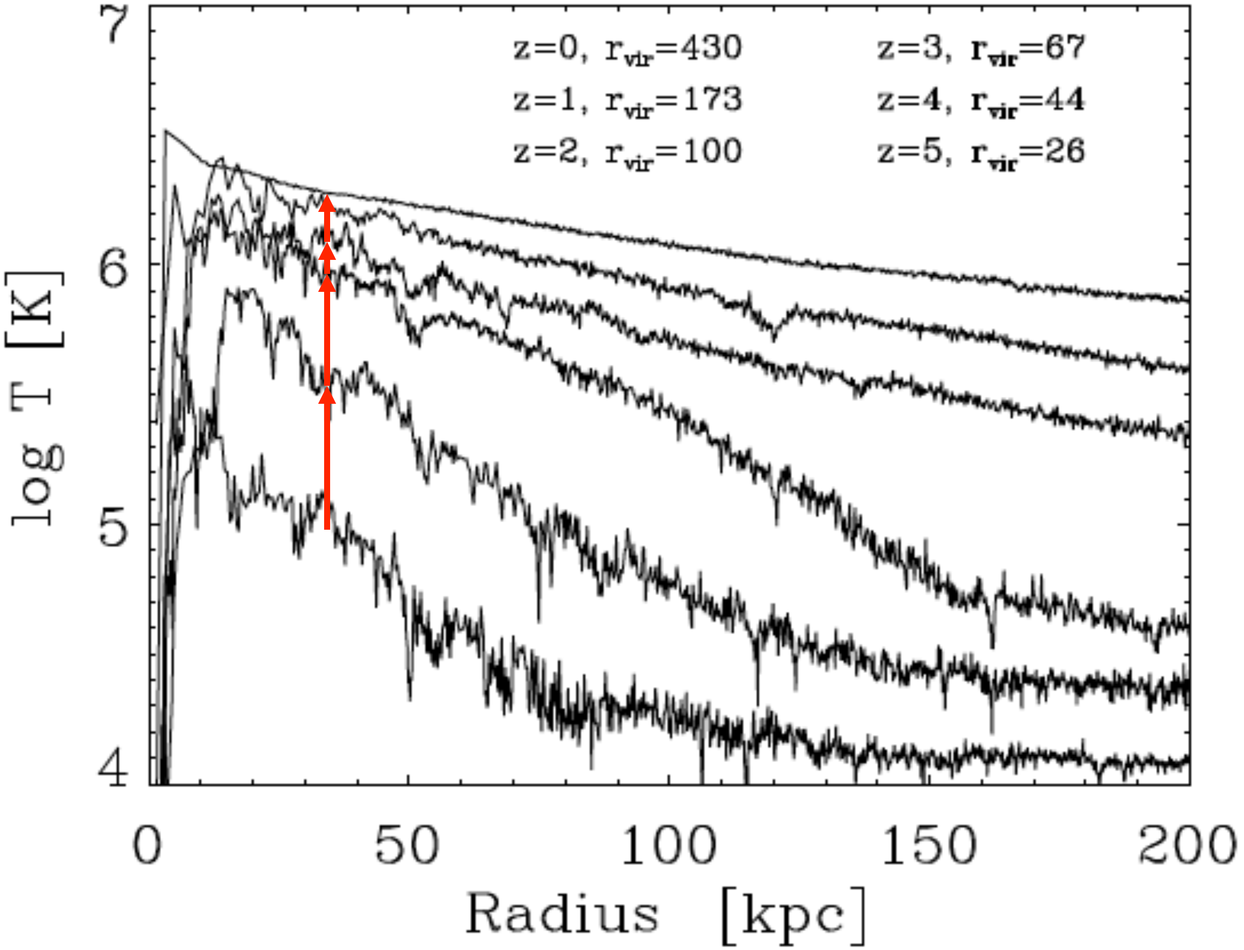


FIG. 3.— Time evolution of the gas temperature profile from $z = 5$ to $z = 0$ (from bottom to top) for halo A (200^3 resolution). The average temperature of the gas is steadily increasing. At the end of its initial formation phase at $z \approx 2$ the galaxy is surrounded by a halo of hot gas heated to the virial temperature.

Physics - why does gas not cool?

- Gas is steadily being heated by in-falling new gas (-PdV and Tds).
- “Dynamical Friction” due to in-falling stellar lumps is very important for evolution of the stellar and DM components.
- Of course “feedback” from central black holes and from supernovae also exists and must be complementary to effects listed above (and this is now being added to the codes – thesis projects).

Minor Mergers Dominate the Accretion

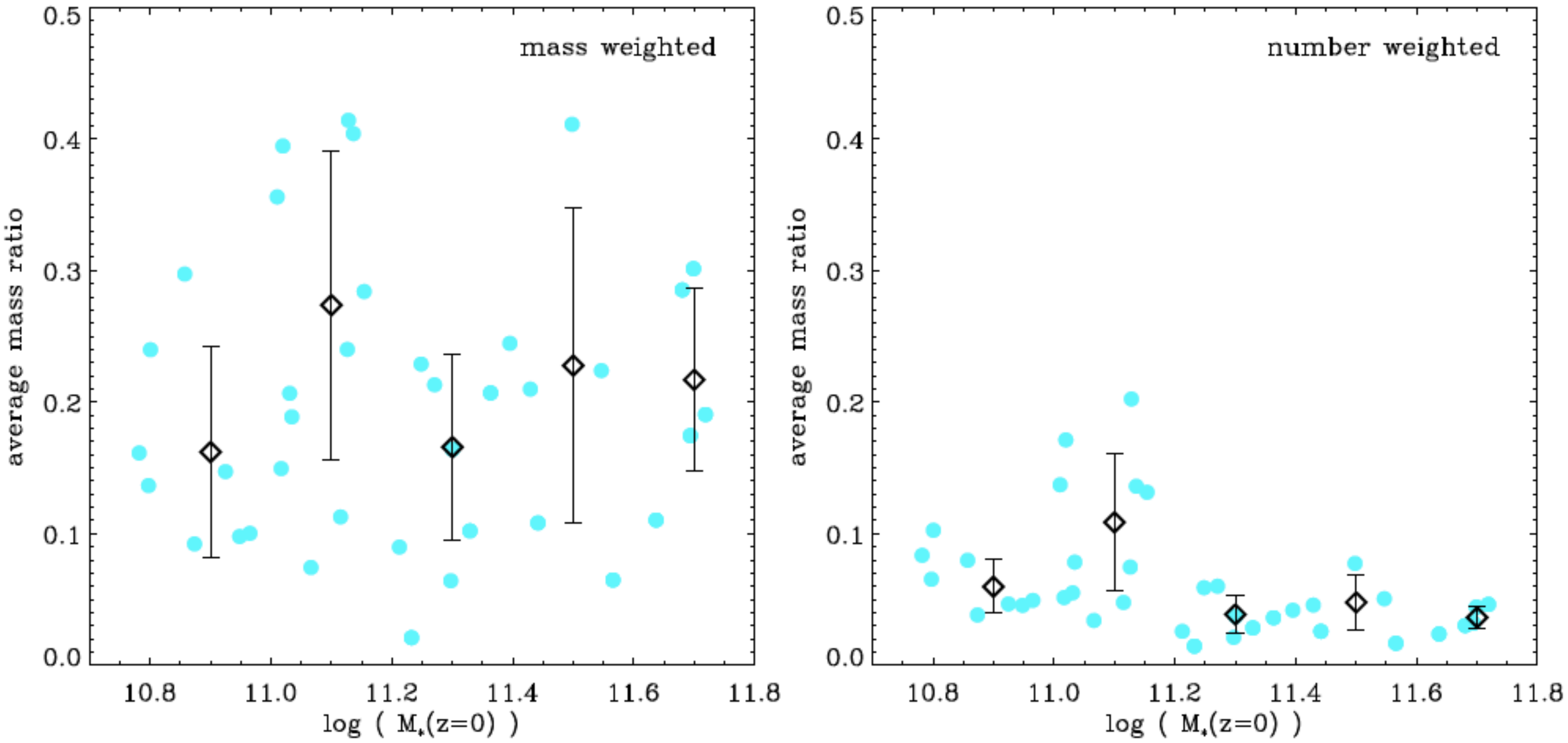
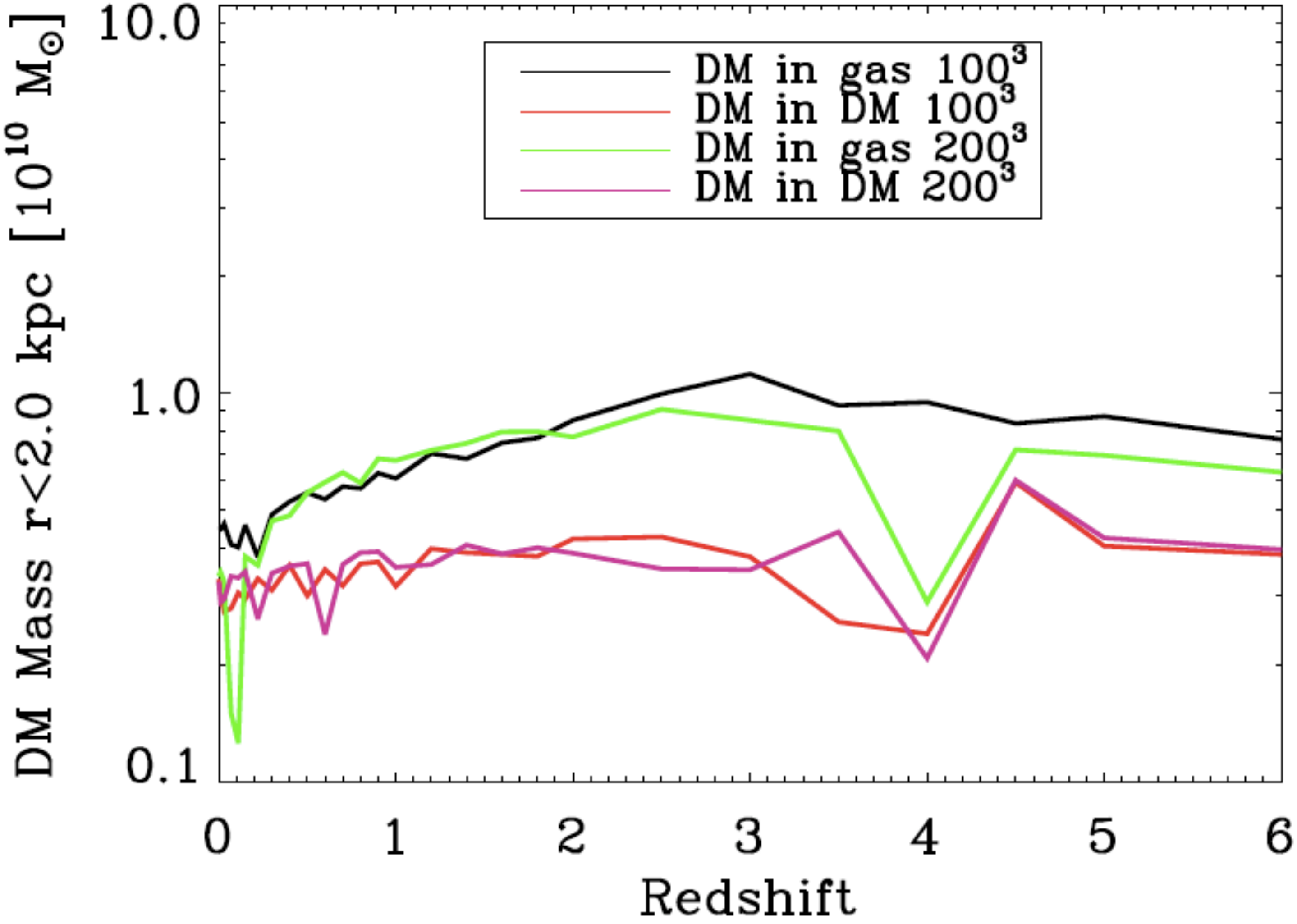


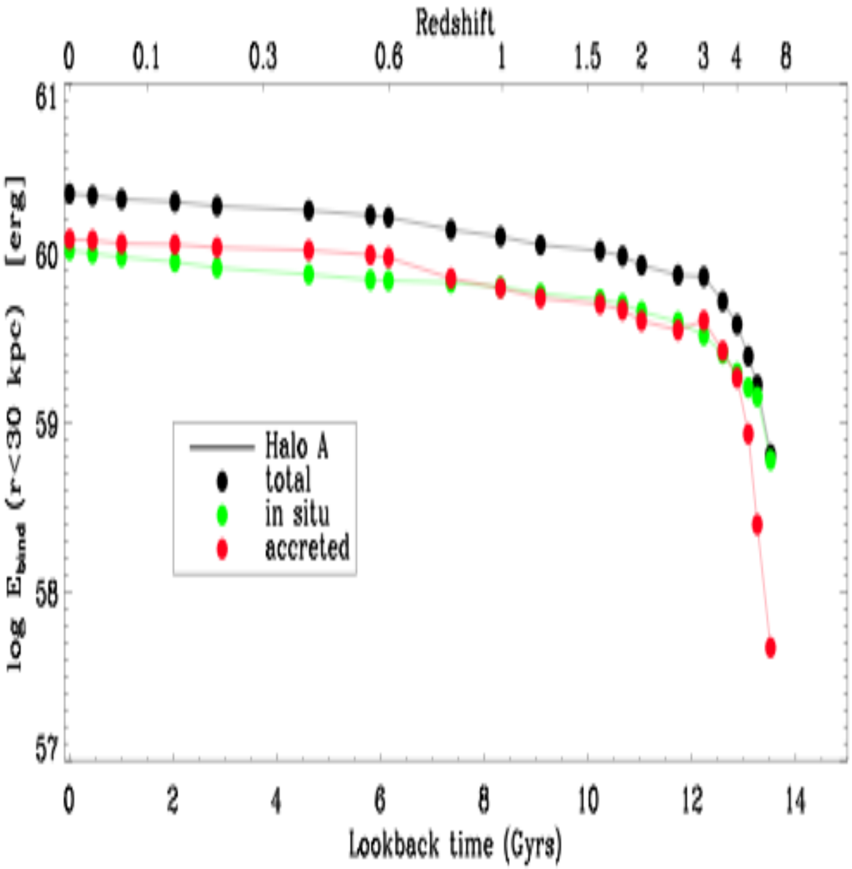
FIG. 5.— Left: The average mass-weighted stellar merger mass-ratios (since z=2) as a function of present-day galaxy mass (blue dots). The black diamonds show the binned averages within 0.2 dex in stellar mass with the one sigma error bars. Trends with galaxy mass are statistically not significant. The mass growth is dominated by minor mergers with a mass ratio of ≈ 1:5. Right: The average number-weighted merger mass-ratio (for all stellar mergers since z=2) as a function of present-day galaxy mass. There is a weak trend for more massive galaxies to experience relatively more minor mergers. On average most stellar mergers have mass-ratio of ≈ 1 : 16.

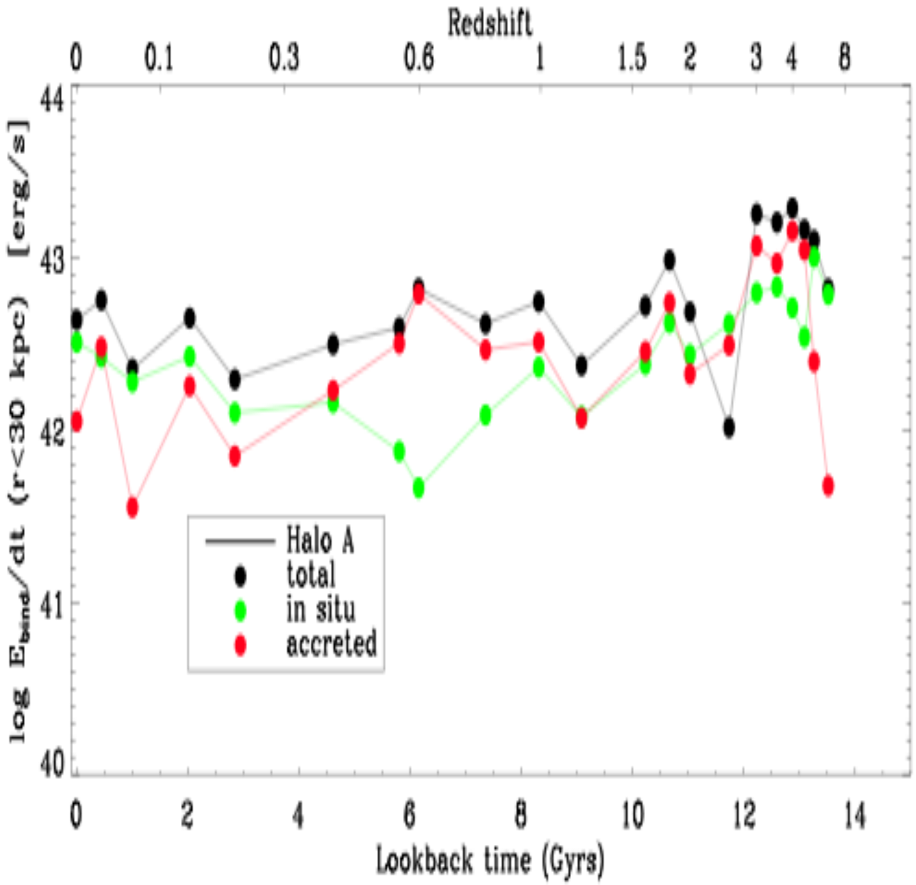
Dark Matter Evolution - density declines in second phase



Binding Energy ~ 10^{60} erg from both in-situ and accreted stars - “gravitational heating”:

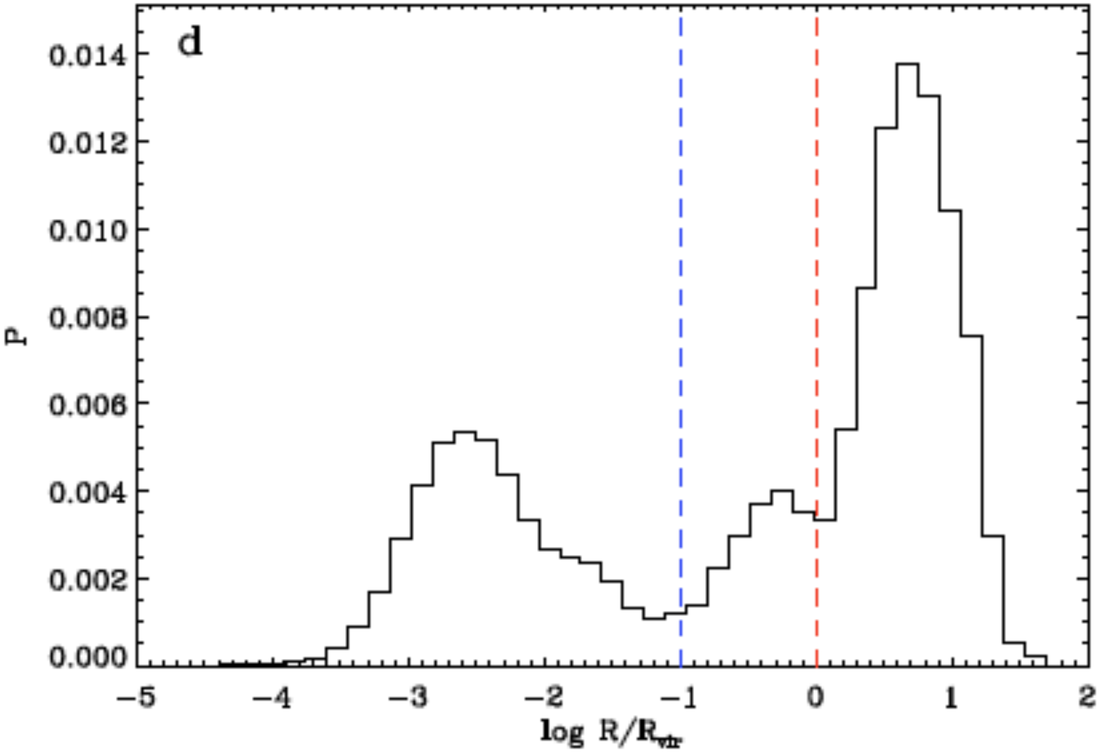
- In-situ energy is radiated,
- - Accreted energy heats gas and pushes out DM

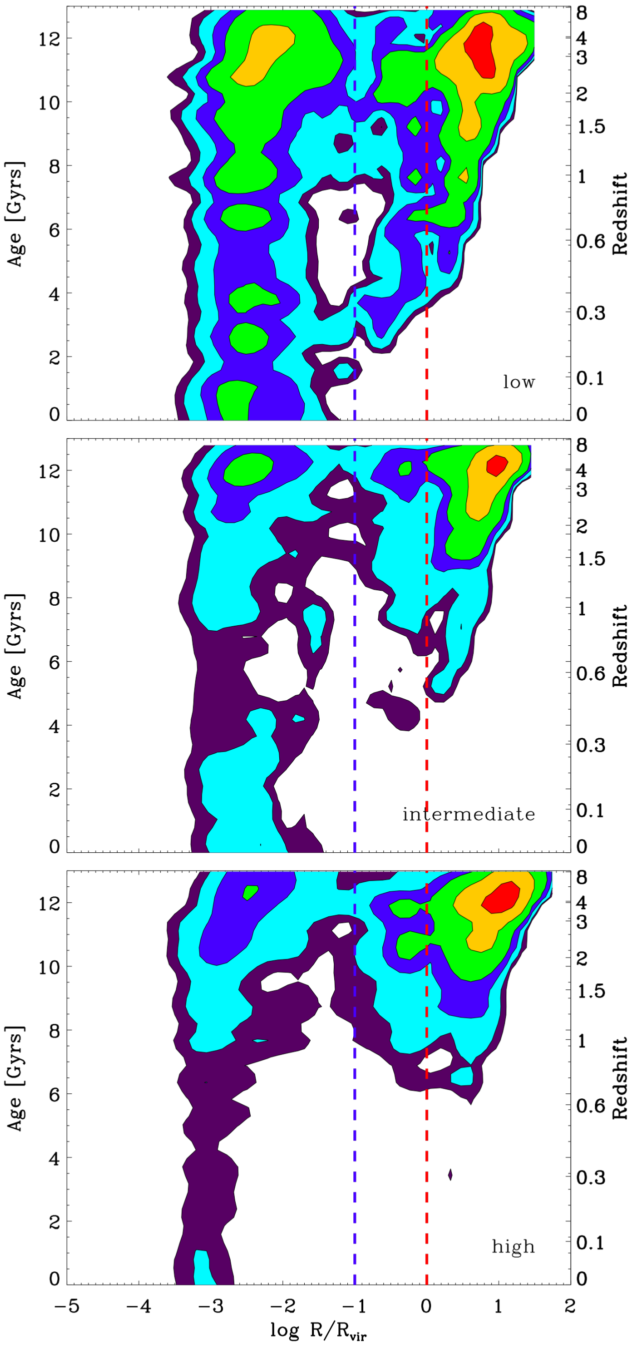




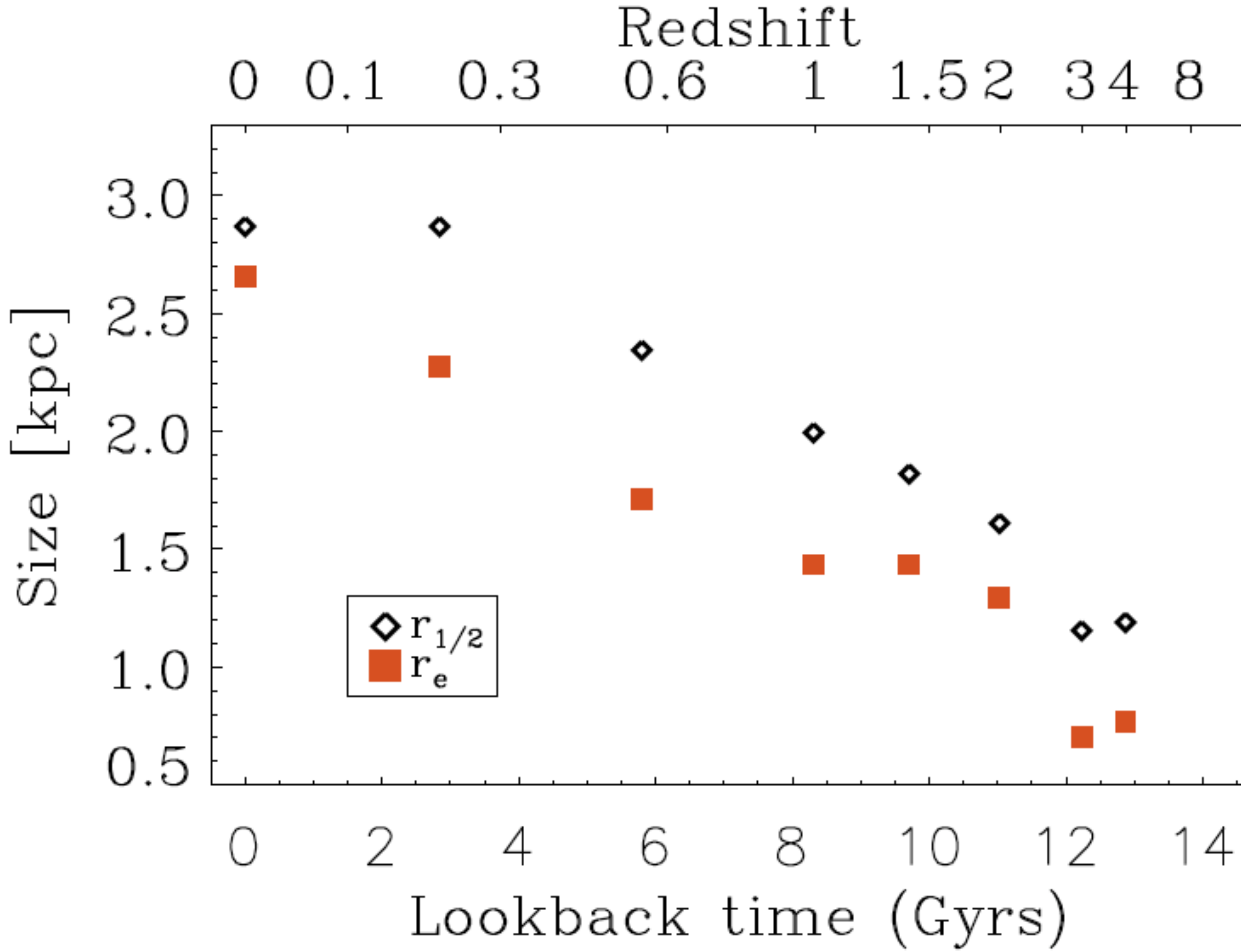
Where & when are stellar particles made?

First attempt at
showing data from a set of
100^3 simulations
(L.Oser, Naab…)





Size evolution - substantial growth (observed and computed); what is the cause?



More Massive Systems are Older

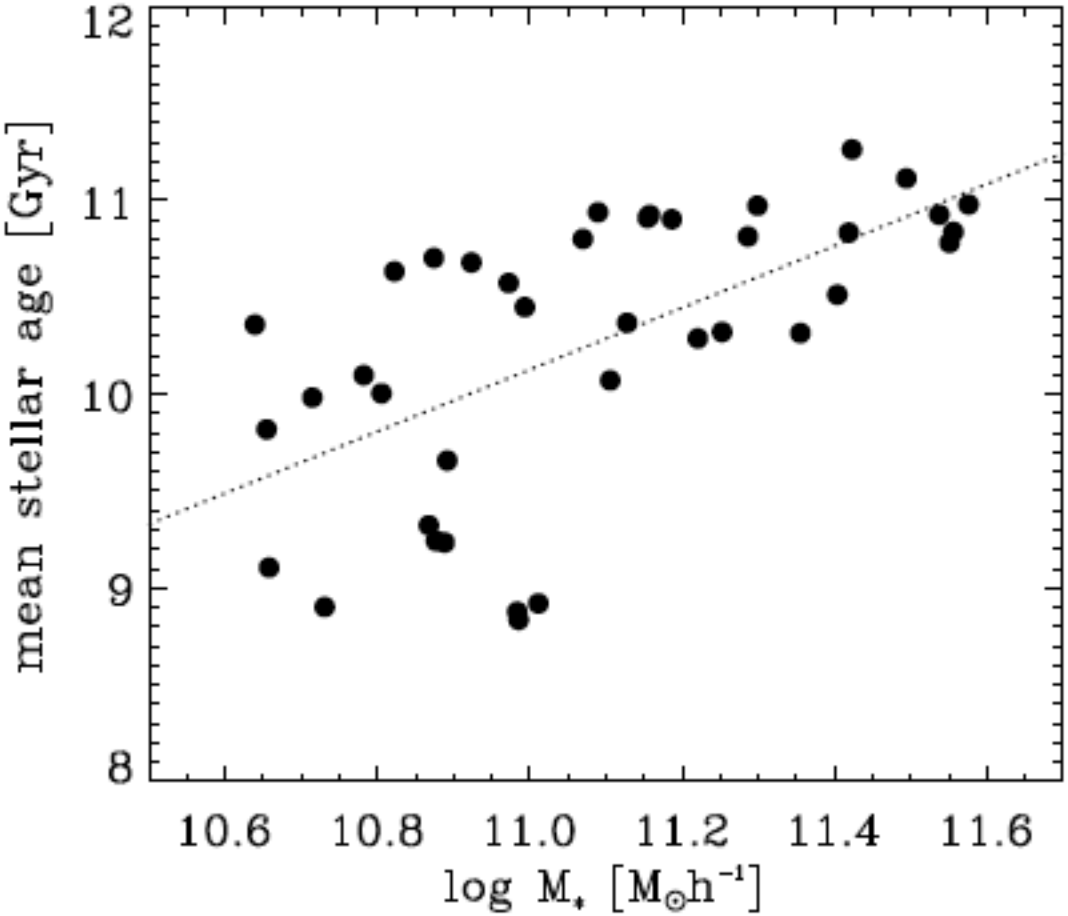
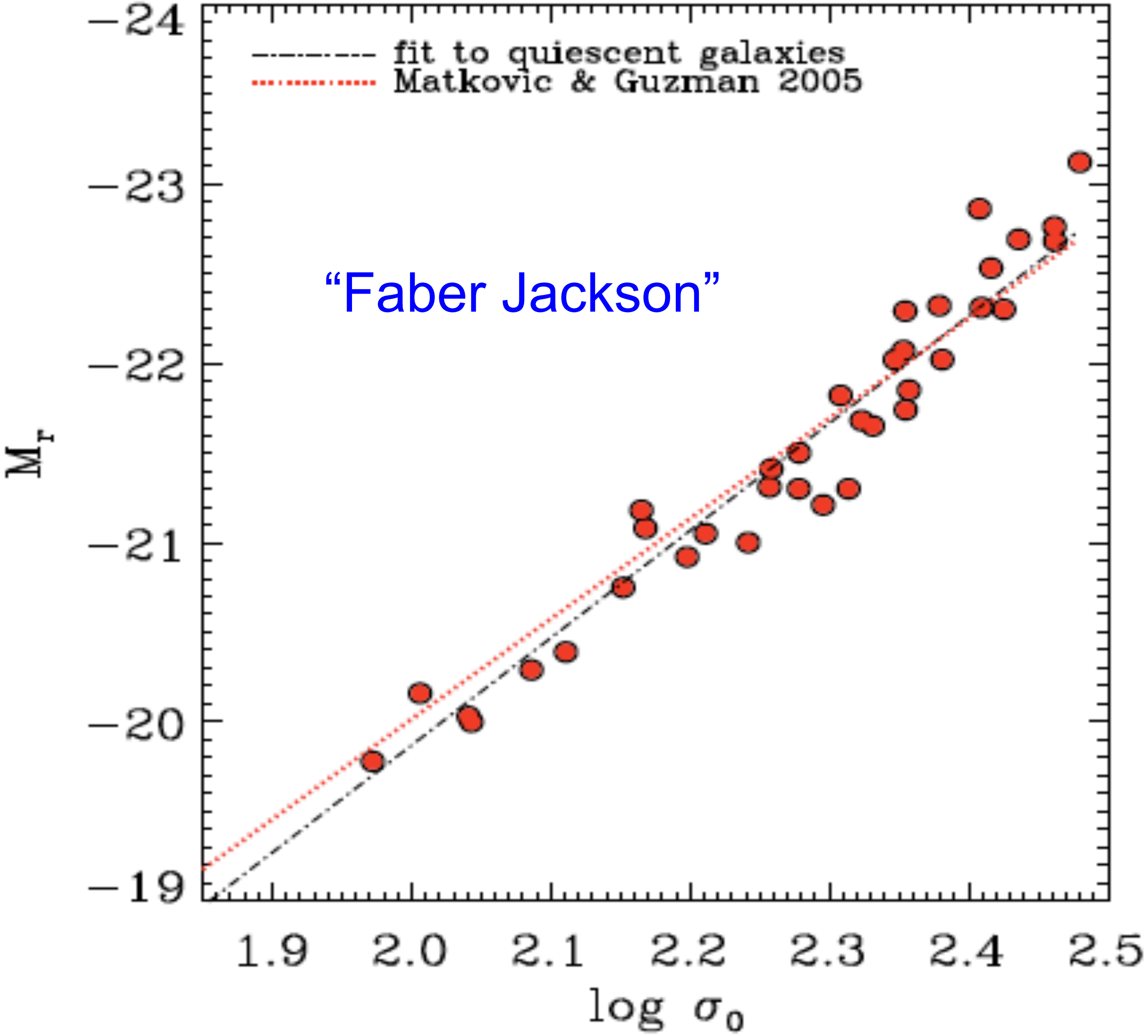


FIG. 12.— Mean age of the stars inside r_{10} as function of galaxy mass. High mass galaxies consist of older stars than the low mass galaxies, recovering the phenomenon usually referred to as 'archaeological downsizing' ($t_{mean} \propto \log M_*^{1.6}$).

Fit to observations is good



What have we learned? Old news.

- For massive systems the 1977 work of Binney, Silk and Rees & Ostriker appears to be correct :

Cooling time of gas becomes longer than the dynamical time and star formation ceases. Systems live in hot bubbles and then grow by accretion of smaller stellar systems.

3) Why is there a dramatic evolution of size? 4) Why is galaxy “red and dead” early but continues to grow in luminosity?

- Evolution of size is apparent, not real. Both components keep roughly constant in size, but mean size grows as accreted material dominates.
- During the second phase, the luminosity and stellar mass may double but very few stars are formed.

Simplest Physical Modeling - via Virial Theorem

- Make initial, stellar system dissipatively from cold gas with gr radius $\mathbf{R_I}$, Mass $\mathbf{M_I}$, velocity dispersion $\mathbf{< V_I^2>}$ & energy $\mathbf{E_I}$:
  - $\mathbf{E_I = - 0.5\ G\ M_I^2 / R_I = -0.5\ M_I < V_I^2>}$
- Add stellar systems conserving energy with total Mass $\mathbf{M_A = \eta\ M_I}$, velocity dispersion $\mathbf{< V_A^2> = \varepsilon < V_I^2>}$ & energy $\mathbf{E_A}$:
  - $\mathbf{E_A = -0.5\ M_I < V_I^2> \eta\ \varepsilon}$

- To make combined stellar system with grav radius $\mathbf{R_F}$, Mass $\mathbf{M_F = M_I(1 + \eta)}$, velocity dispersion $\mathbf{< V_F^2 >}$ & energy $\mathbf{E_F}$:
  - $\mathbf{E_F = - 0.5\ G\ M_F^2 / R_F = -0.5\ M_I < V_F^2 >(1+ \eta)}$
- Then, equating total initial and final states
  - $\mathbf{E_F = E_I + E_A}$, gives for the ratios of the in-situ to the ultimate state as follows:

  - $(< V_F^2 >/ < V_I^2 >) = [\ (1 + \eta\ \varepsilon) / (\ 1 + \eta)\ ]$
  - $(R_F / R_I) = [\ (1 + \eta)^2 / (\ 1 + \varepsilon\ \eta)\ ]$
  - $(\Sigma_F / \Sigma_I) = [\ (1 + \eta\ \varepsilon)^2 / (\ 1 + \eta)^3\ ]$

“major mergers”

-> $\varepsilon = 1$

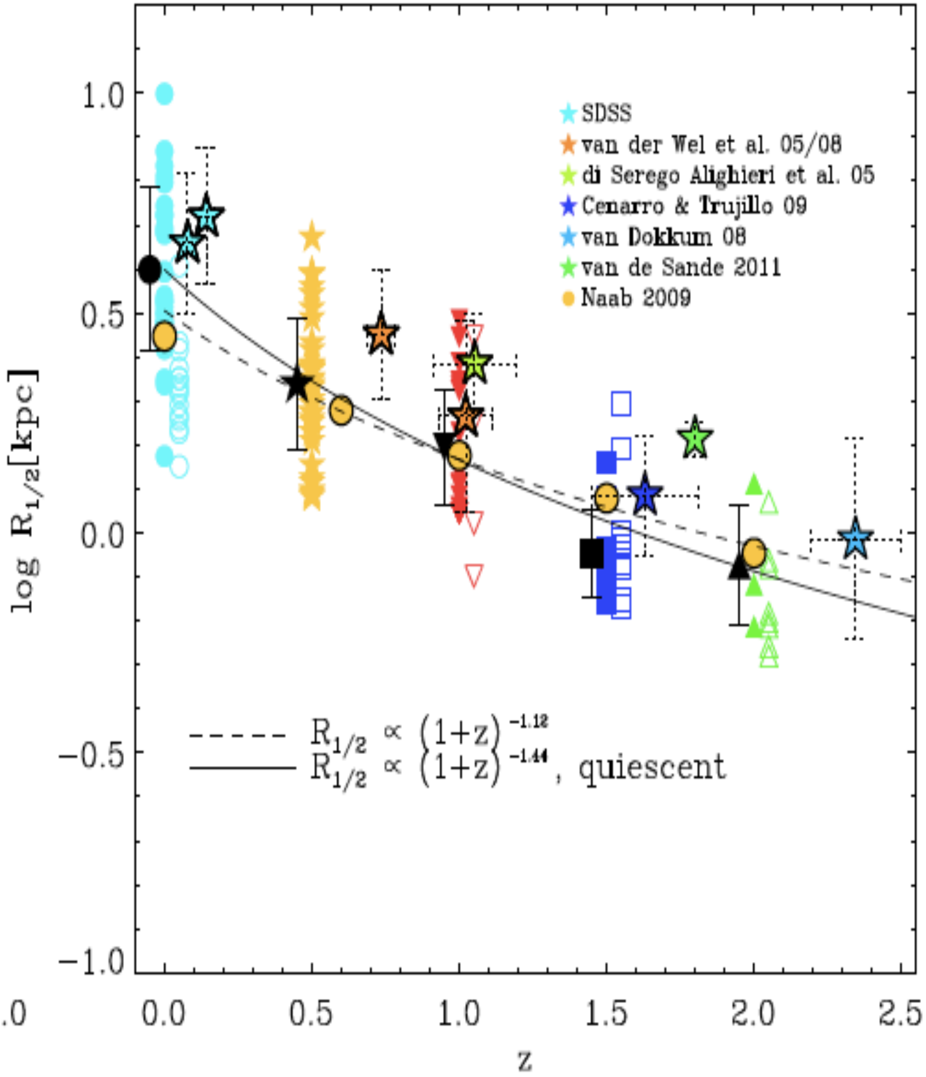
formulae reduce to the classic result,

BUT

If minor then

-> $\varepsilon \ll 1$,

velocity dispersion declines, the surface density declining dramatically, as in the numerical simulations.



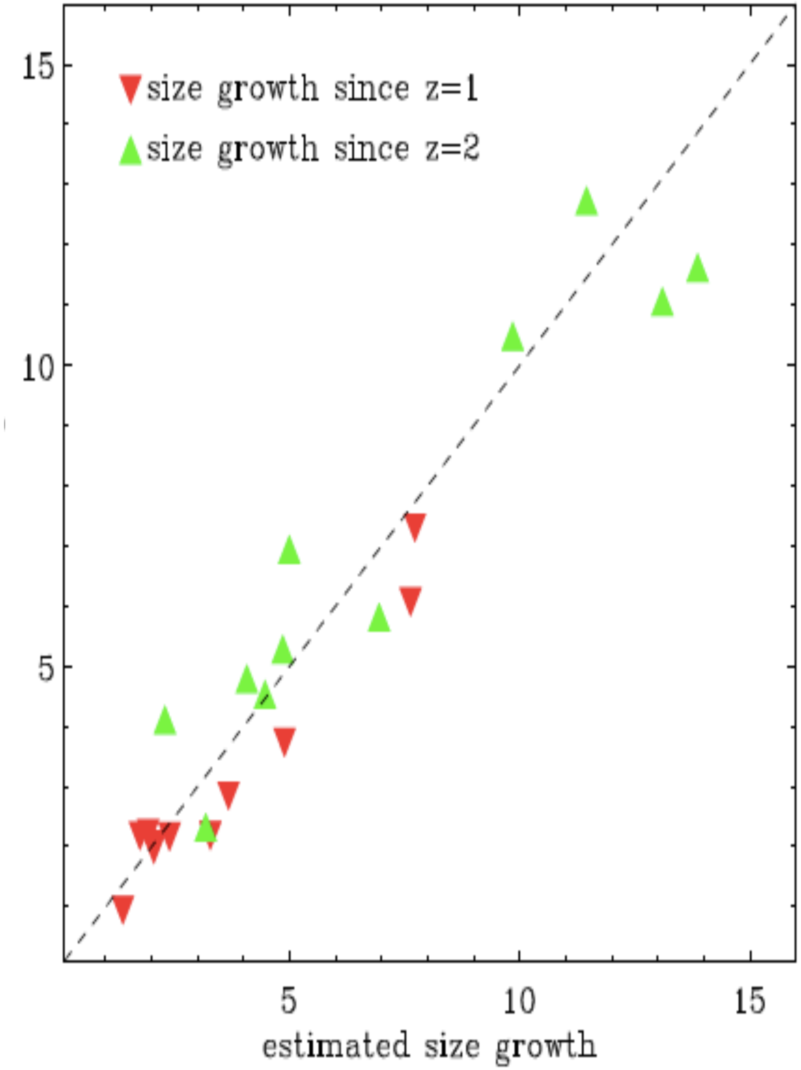


FIG. 5.— The size growth predicted by equation 1 in combination with the stellar merger histories compared to the actual size growth in the simulations of the galaxies more massive than $M_* = 6.3 \times 10^{10} M_\odot$ at z=2. The green triangles indicate the evolution between z=2 and z=0 the red triangles the evolution between z=1 and z=0. The simple virial estimate is a good predictor for the actual size evolution.

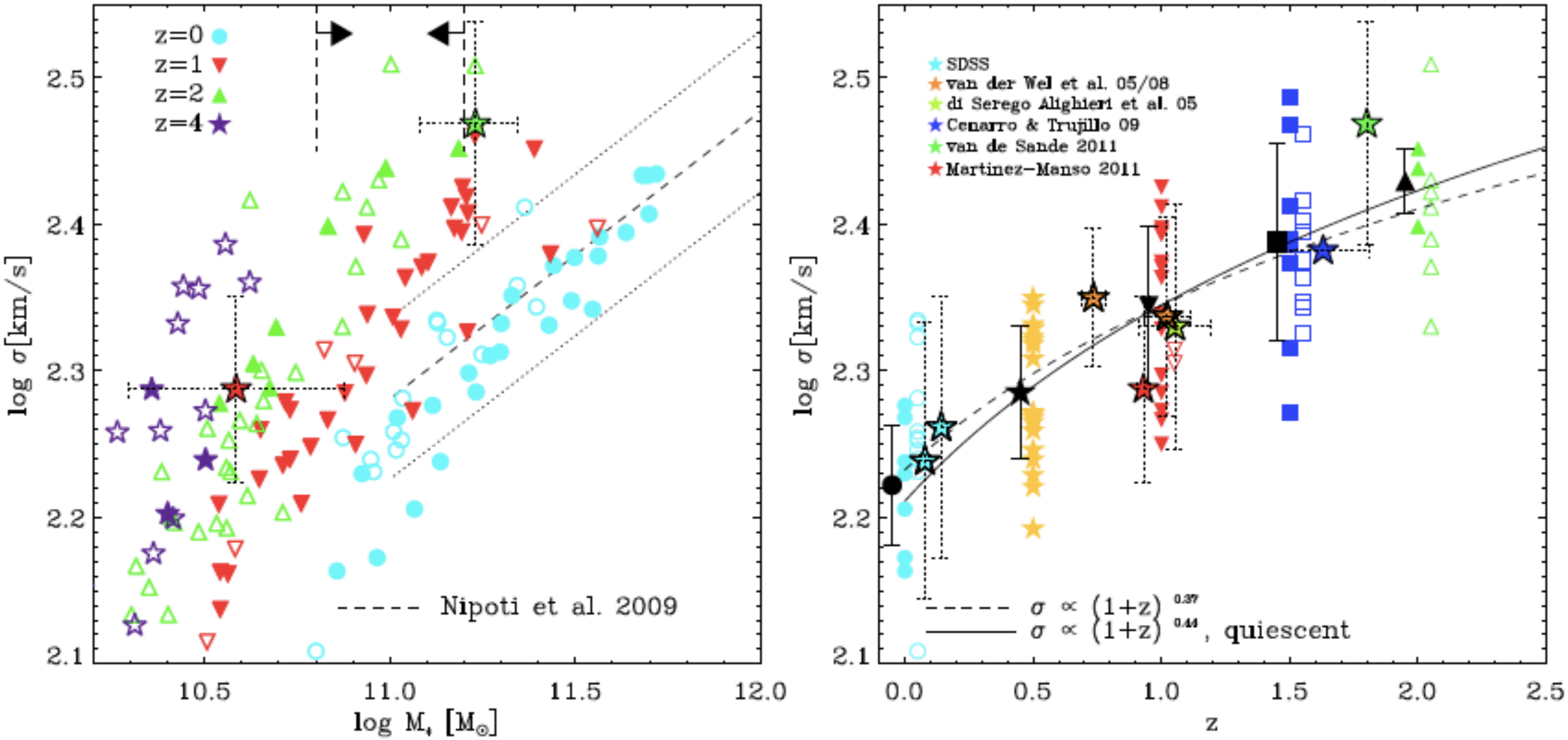


FIG. 4.— Central (within 0.5 $R_{1/2}$) projected velocity dispersion as a function of stellar mass at z=0 (blue circles), z=1 (red triangles), z=2 (green triangles) and z=4 (purple stars). The relation for local galaxies from Nipoti et al. (2009) are shown by the dashed line with the dotted lines indicating the scatter of the observed galaxies. At a given mass the velocity dispersion decreases significantly from z=4 to z=0. The mass limits used for the right plot are indicated by the vertical dashed lines. Right: Central projected velocity dispersion of the simulated galaxies with masses in the range of $6.3 \times 10^{10} M_\odot < M_\star < 1.6 \times 10^{11} M_\odot$ at any given redshift as a function of redshift. Solid symbols represent star forming galaxies and empty symbols show quiescent systems (offset by 0.1 in redshift for clarity). Observational estimates from different authors are given by the solid star symbols (see Cenarro & Trujillo 2009; van de Sande et al. 2011; Martinez-Manso et al. 2011) with the observed scatter given by the dotted error bars, where available. The black lines show the result of a power law fit for all (dashed line) and the quiescent (solid line) galaxies, respectively. The simulations indicate a mild dispersion evolution from ≈ 262 kms^{-1} at z=2 to ≈ 177 kms^{-1} at z=0, in agreement with observations.

Conclusions: High Mass Systems

- High resolution SPH simulations without feedback produce normal, massive but small elliptical galaxies at early epochs from in-situ stars made from cold gas.
- Accreted smaller systems add, over long times, a lower metallicity stellar envelope of debris (obvious test exists).
- The physical basis for the cutoff of star-formation is gravitational energy release of in-falling matter acting through -PdV and +Tds energy input to the gas.
- This simple two phase process explains the decline in velocity dispersion and surface brightness at later times.
- Feedback from SN and AGN are real phenomena - but secondary and mainly important for clearing out gas at late times and reducing stellar mass as compared to the simulations.

Primary cause of mass growth

- Early times and low mass galaxies:
  - ***Gas inflows.***
- Late times and high mass galaxies:
  - ***Accretion of satellites.***

[*In neither period is it major mergers.*