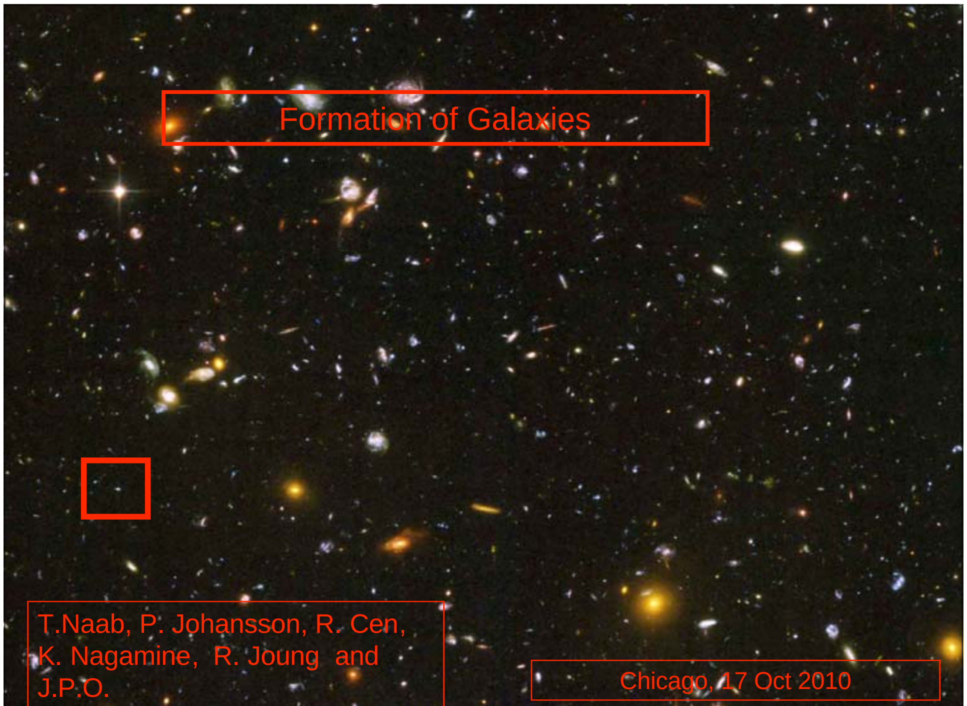
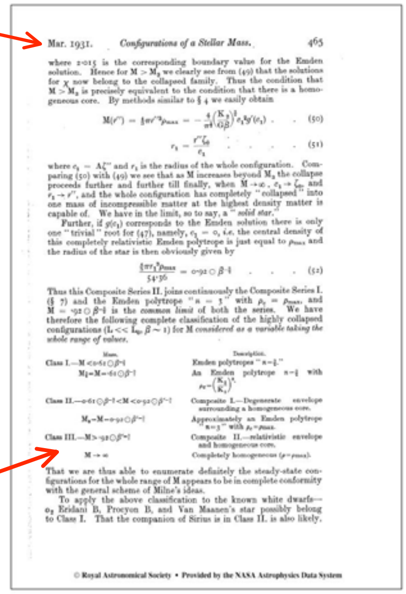


A Personal Aside

- 1959: Graduate Harvard w AB in Chemistry and Physics. Astronomy tried and awful. What do do? Draft.
- 1960: Work at Naval Research Lab in DC. Find article on Chandra in Fortune Mag. Wow!
- 1961: Move to Williams Bay Wisc & UC PhD study and learn that Chandra no longer takes astro students.
- 1962-64: PhD with S. Chandrasekhar (polytropes).
- 1965: NSF postdoctoral fellowship in Camb w DLB.
- 1966: PUO assistant prof, work w Spitzer.

Digression: Chandra's first (MNRAS.91.446C. 3/31) paper. ***No*** maximum mass and a thank-you to Milne.



Mar. 1931. *Configurations of a Stellar Mass.* 465

where 2·015 is the corresponding boundary value for the Emden solution. Hence for $M > M_3$ we clearly see from (49) that the solutions for χ now belong to the collapsed family. Thus the condition that $M > M_3$ is precisely equivalent to the condition that there is a homogeneous core. By methods similar to § 4 we easily obtain

$$M(r'') = \frac{4}{3}\pi r''^3 \rho_{max} = -\frac{4}{\pi^{\frac{1}{2}}}\left(\frac{K_2}{G\beta}\right)^{\frac{3}{2}} e_1^2 y'(e_1) \quad . \quad . \quad (50)$$

$$r_1 = \frac{r''\zeta_0}{e_1} \quad . \quad . \quad . \quad . \quad (51)$$

where $e_1 = A\zeta''$ and r_1 is the radius of the whole configuration. Comparing (50) with (49) we see that as M increases beyond M_3 the collapse proceeds further and further till finally, when $M \to \infty$, $e_1 \to \zeta_0$, and $r_1 \to r''$, and the whole configuration has completely "collapsed" into one mass of incompressible matter at the highest density matter is capable of. We have in the limit, so to say, a "*solid star*."

Further, if $y(e_1)$ corresponds to the Emden solution there is only one "trivial" root for (47), namely, $e_1 = 0$, *i.e.* the central density of this completely relativistic Emden polytrope is just equal to ρ_{max} and the radius of the star is then obviously given by

$$\frac{\frac{4}{3}\pi r_1^3 \rho_{max}}{54{\cdot}36} = 0{\cdot}92 \odot \beta^{-\frac{3}{2}} \quad . \quad . \quad . \quad (52)$$

Thus this Composite Series II. joins continuously the Composite Series I. (§ 7) and the Emden polytrope "$n = 3$" with $\rho_c = \rho_{max}$, and $M = {\cdot}92 \odot \beta^{-\frac{3}{2}}$ is the *common limit* of both the series. We have therefore the following complete classification of the highly collapsed configurations ($L << L_E$, $\beta \sim 1$) for M *considered as a variable taking the whole range of values.*

Mass.	Description.
Class I.—$M < 0{\cdot}61 \odot \beta^{-\frac{3}{2}}$	Emden polytropes "$n = \frac{3}{2}$."
$M_1 = M = {\cdot}61 \odot \beta^{-\frac{3}{2}}$	An Emden polytrope $n = \frac{3}{2}$ with $\rho_c = \left(\frac{K_2}{K_1}\right)^3$.
Class II.—$0{\cdot}61 \odot \beta^{-\frac{3}{2}} < M < 0{\cdot}92 \odot \beta^{-\frac{3}{2}}$	Composite I.—Degenerate envelope surrounding a homogeneous core.
$M_3 = M = 0{\cdot}92 \odot \beta^{-\frac{3}{2}}$	Approximately an Emden polytrope "$n = 3$" with $\rho_c = \rho_{max}$.
Class III.—$M > {\cdot}92 \odot \beta^{-\frac{3}{2}}$	Composite II.—relativistic envelope and homogeneous core.
$M \to \infty$	Completely homogeneous ($\rho = \rho_{max}$).

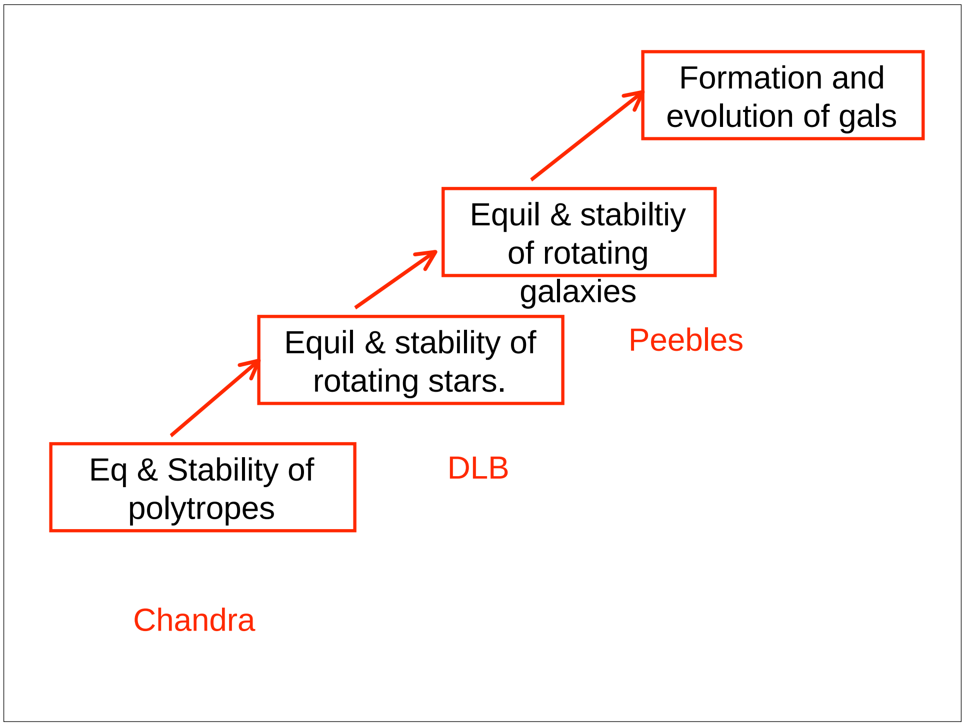
That we are thus able to enumerate definitely the steady-state configurations for the whole range of M appears to be in complete conformity with the general scheme of Milne's ideas.

To apply the above classification to the known white dwarfs—o_2 Eridani B, Procyon B, and Van Maanen's star possibly belong to Class I. That the companion of Sirius is in Class II. is also likely.

Chandrasekhar published three papers in 1931

Learning From Chandra

- A) Astrophysics stands on physics and good physics should underlie all all astrophysics calcs.
- B) Pay attention to students; it is good for you and good for them!
- C) He was a workaholic. There is a lesson there.
- D) Range. No need to stick to one field. He worked, wrote and moved on.
- ------Characteristics I admired but could not model-----
- *Elegance, wit, grace, ability to make difficult calcs*



Approaches to Galaxy Formation

- A) *Archeological astrophysics*: look at the local components, disc, bulge, halo etc in our and other galaxies and speculate on formation, *eg* ELS. Gain knowledge: 1960s – 70s.
- B) *Toy physics problems*: do mergers, accretion study of orbits etc. Gain insight: 1980s – 90s
- C) ----- Enter cosmology, growth of structure ---------
- D) *Dark matter calculations*: paint on galaxies, the “semi-analytic method”. Useful first try: 2000s
- E) *Hydro-dynamical calculations:* in a cosmological setting. The cosmological “zoom” mode: 2005 ->

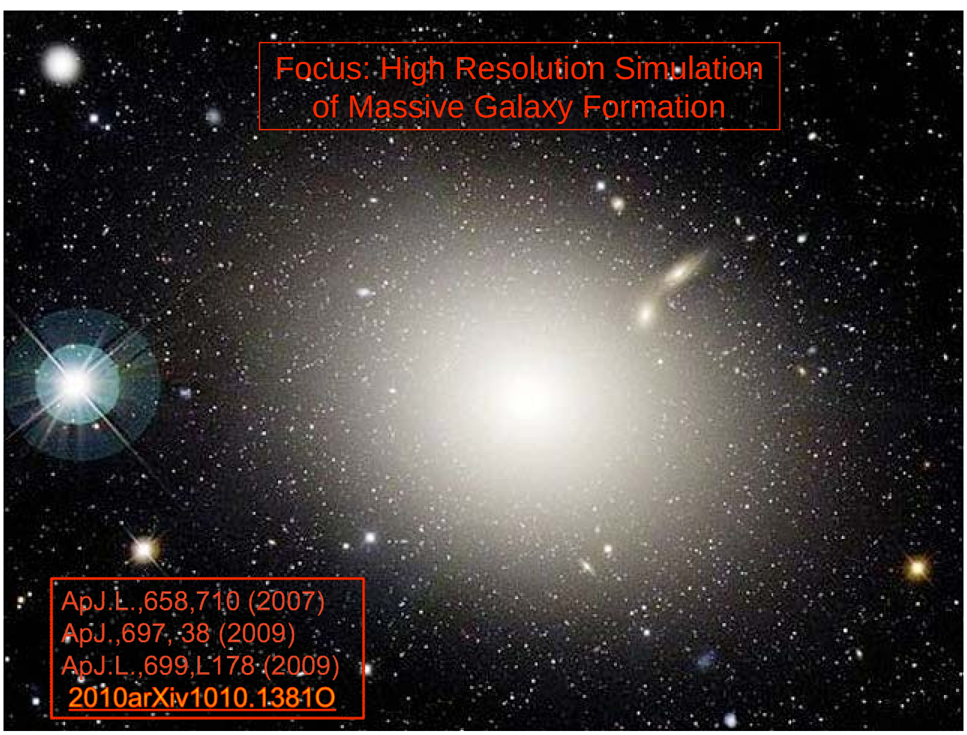
The Questions ?

Can we start with initial conditions taken from the now standard model of cosmology, add standard physics, compute forwards and end with galaxies like those we see about us?

Predictive and falsifiable. It could fail!
[Unlike the “semi-analytic” method]

What ingredients in physics are essential?

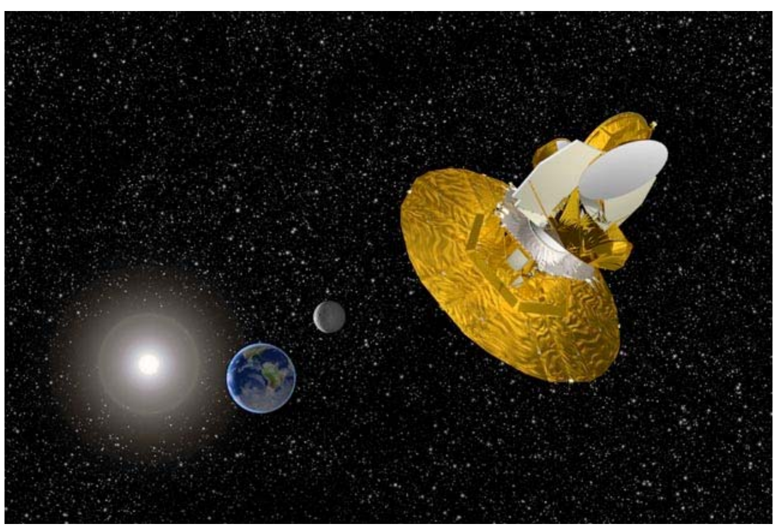
Focus on massive galactic systems – giant ellipticals.



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

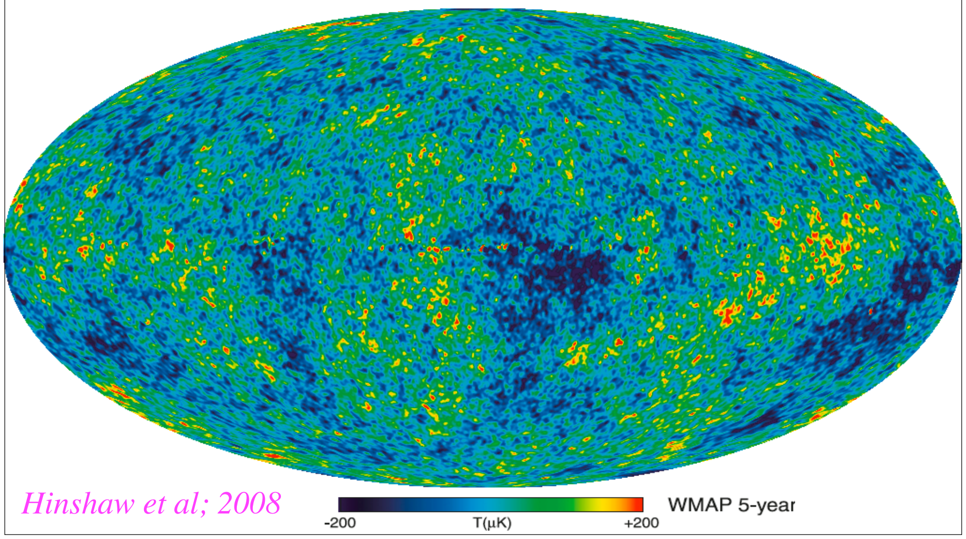
- Giant elliptical galaxies form early and grow in size and mass without much late star-formation.
- Major mergers are uncommon at late times (or else disk galaxies would have been destroyed).
- Dark matter does not dominate the inner parts of elliptical galaxies.
- Half of all metals are ejected from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

Ab initio approach: WMAP (2002-2010)



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

Cosmological Simulation: Start with WMAP CBR Sky

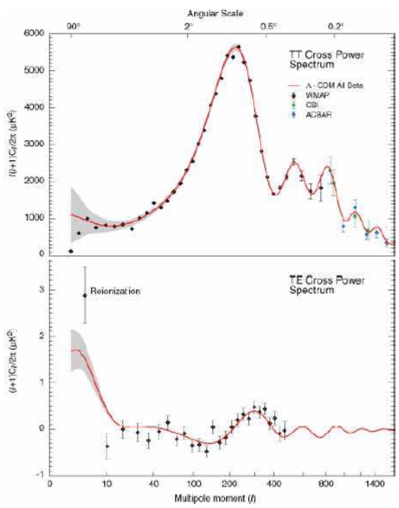


Hinshaw et al; 2008

WMAP Spectrum of Cosmic Perturbations

(Amplitude)^2

(Aplitude)^2



Spherical Harmonic

In Detail: Best Current Cosmological Model (prior: ΛCDM)

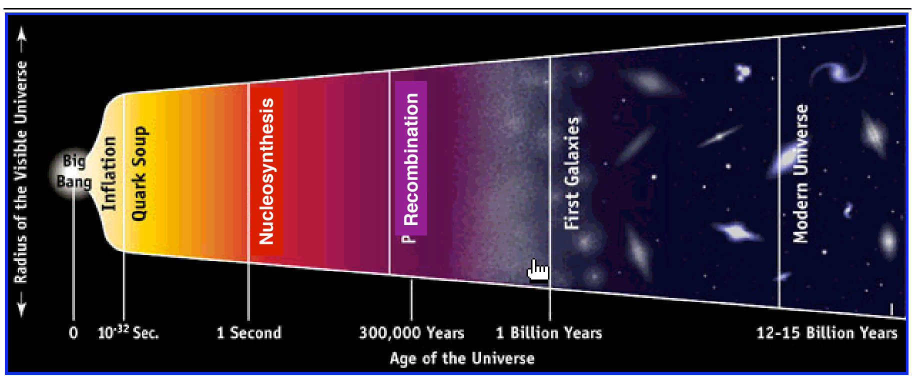
- Ω_{tot} = 1, ~flat geometry [obs =1.010 +0.016]
- Ω_{cdm} = 0.22 ± 0.02
- Ω_{baryon} = 0.044 ± 0.002
- Ω_{lambda} = 0.73 ± 0.03
- n = 0.962 ± 0.015
- H_0 = 71.5 ± 1.5 km/s/Mpc
- σ_8 = 0.80 ± 0.01
- τ_{scat} =0.086 ± 0.002

Tegmark et al (SDSS, 2005); Spergel et al (WMAP5, 2008)

Ignore the details! Note that there are four components and small errors.

How to compute cosmic structure formation?

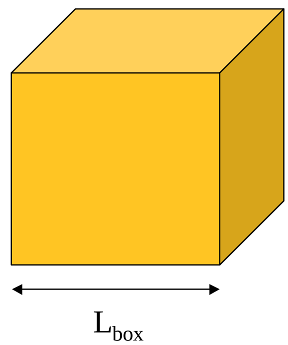
(cartoon version)



linear perturbation theory | nonlinear simulations

Computing the Universe: locally, growth of perturbations computed classically; numerical hydro required to reach the current epoch

- Transformation to *co-moving coordinates* $x=r/a(t)$
- Co-moving cube, periodic boundary conditions
- $L_{box} >> \lambda_{nl}$



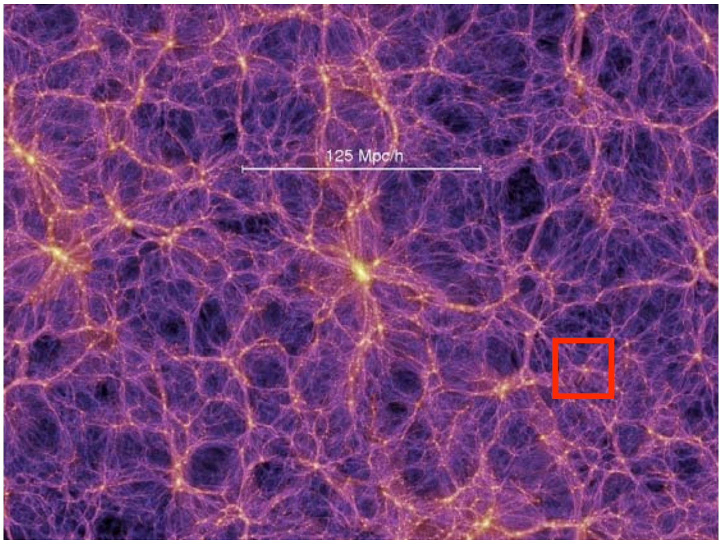
Methods

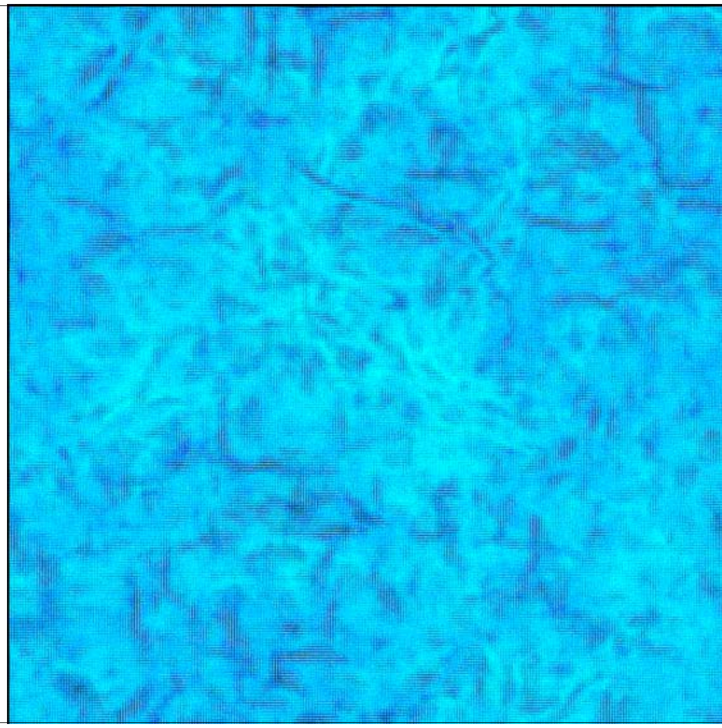
- 1) Particle methods. Put down particles and move according to forces. Now at ~ 1000^3 for DM and ~ 500^3 for "smooth particle hydrodynamics" particles.
- 2) Use fixed mesh. Very efficient ~ 2000^3
- 3) Use adaptive mesh refinement: AMR with four levels each a factor of 8 in mass.
- 4) Use structured mesh.

First Step: Evolution of Dark Matter Component

- 1) Put down particles on a grid (~ 10^9 particles) with slight perturbations of the positions consistent with the early large scale structure given by CBR.
- 2) Give them small velocities consistent with the density structure and the continuity equation.
- 3) Calculate the accelerations of all the particles from Newton's laws (in principle a calculation of order N*(N-1)/2). But algorithms are used which are N*log(N).
- 4) Advance positions and velocities given the velocities and accelerations to find the new distribution of particles.
- 5) Go back to step (3) and iterate to find the evolution of structure.

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





Second Step: hydrodynamic treatment of one piece.

- 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.

What have we learned?

- The onset of 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

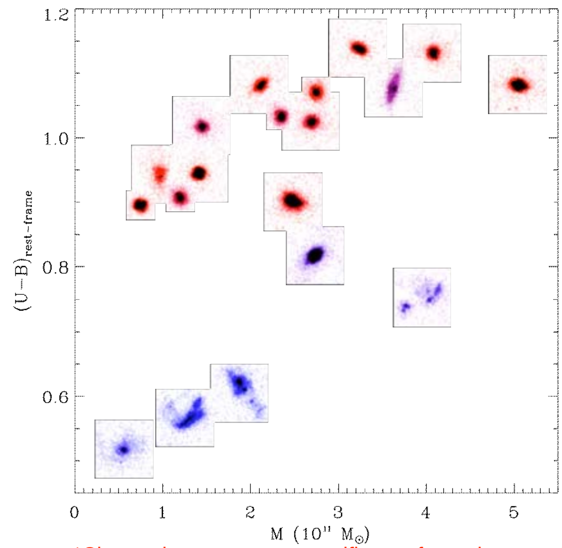
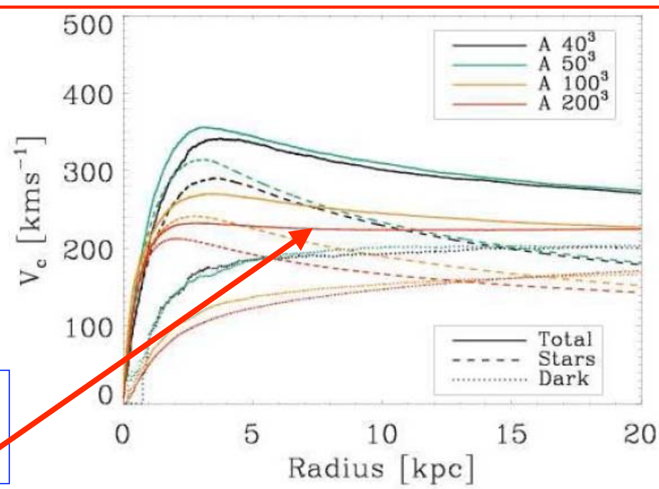


*Chart color represents specific star formation rate: high rate = blue.

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”.

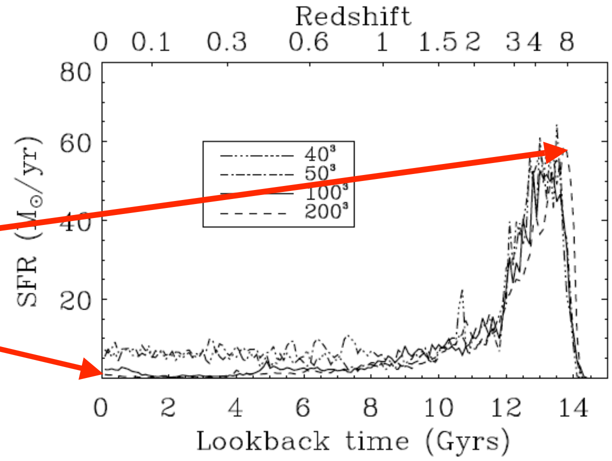


FIG. 2.— Star formation rate (SFR) histories, computed from stellar ages, of galaxy A versus lookback time at four different numerical resolutions: 40^3, 50^3, 100^3, and 200^3 SPH particles and collisionless dark matter particles, respectively. There is a strong trend that the low redshift star formation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

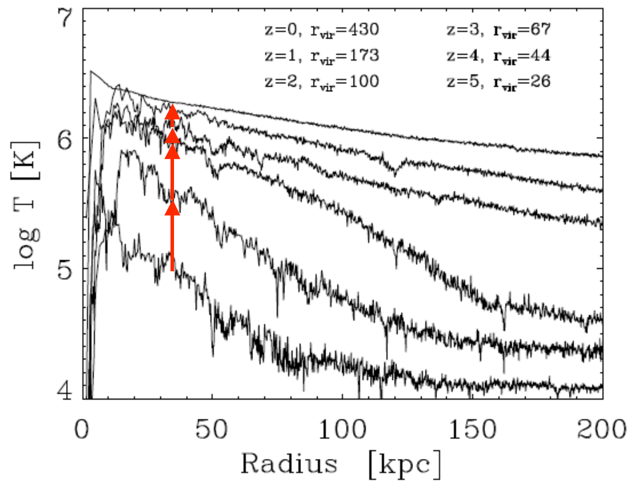
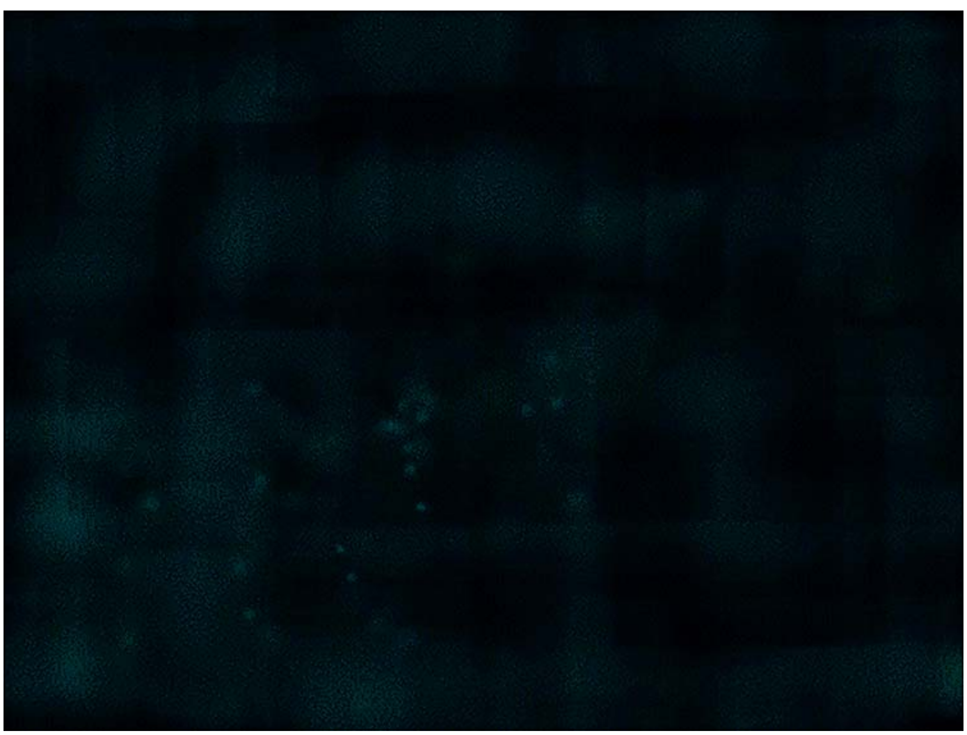


FIG. 3.— Time evolution of the gas temperature profile from $z = 5$ to $z = 0$ (from bottom to top) for halo A (200^3 resolution). The average temperature of the gas is steadily increasing. At the end of its initial formation phase at $z \approx 2$ the galaxy is surrounded by a halo of hot gas heated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

2) Physics - why does gas not cool?

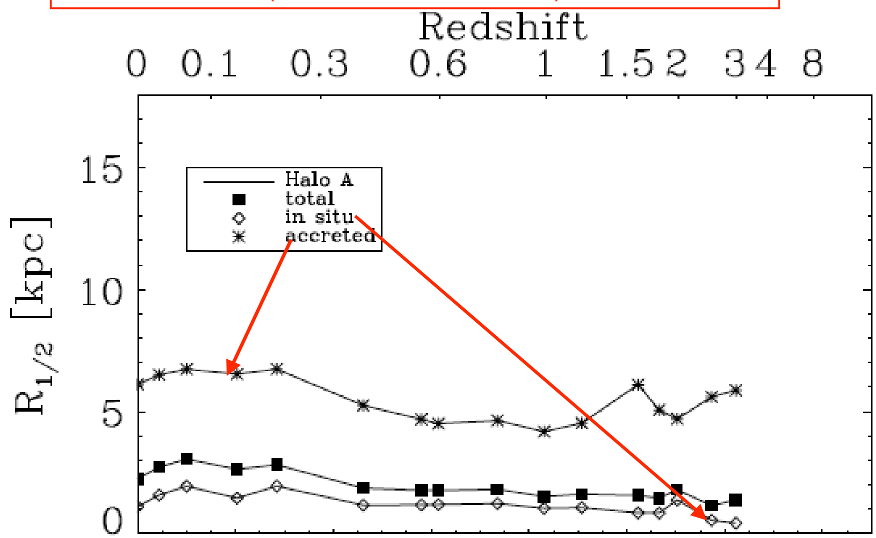
- Gas is steadily being heated by in-falling new gas (-PdV and Tds).
- “Dynamical Friction” due to in-falling stellar lumps is very important for evolution of the stellar and DM components.
- Of course “feedback” from central black holes and from supernovae also exists and must be complementary to effects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



Half-Light Radii of In-situ and Accreted Stars

A Normal Elliptical: fits Sersic Profile

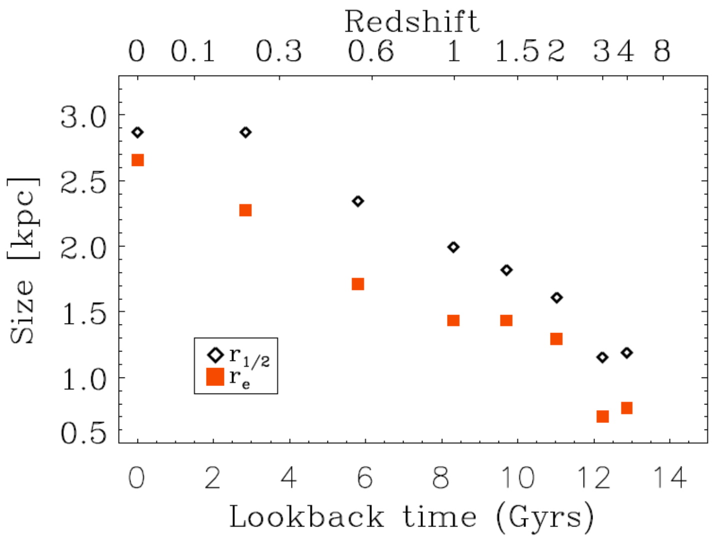
(detailed kinematics ok as well)



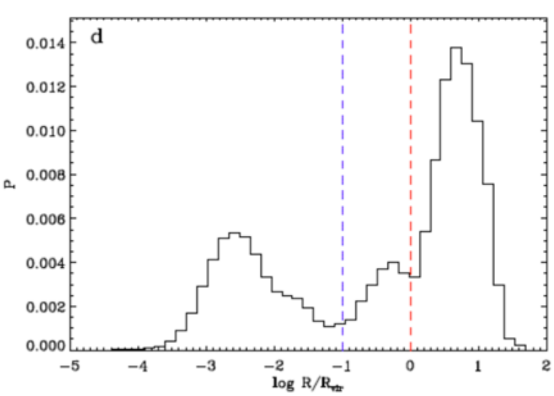
Astronomy

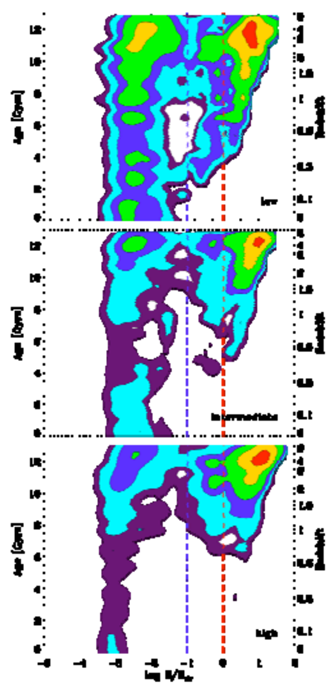
- Two phase growth. First, in-situ star-formation from in-falling cold gas, and then accretion of stellar lumps.
- DM initially increases in density (adiabatic contraction) and then decreases (dynamical friction).
- Metal rich component in center from in-situ star-formation and metal poor component in outskirts due to stellar in-fall of old and small systems.
- Stellar system grows in size with time and central velocity dispersion actually declines with time

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

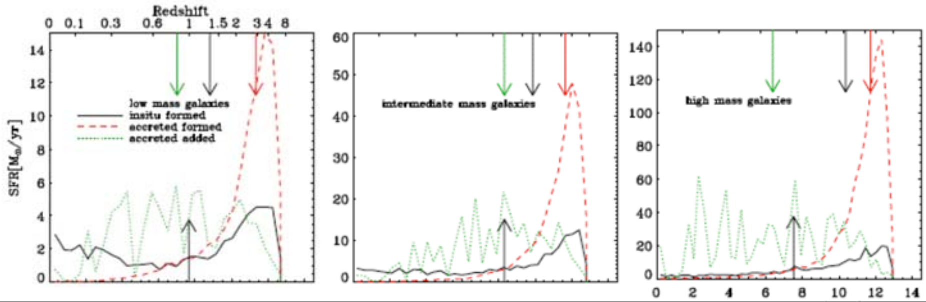


First attempt at
showing data from 100^3
simulation
(L.Oser)





Assembly of galaxies:
Stellar material from minor mergers is made at early times and added at late times.



More Massive Systems are Older

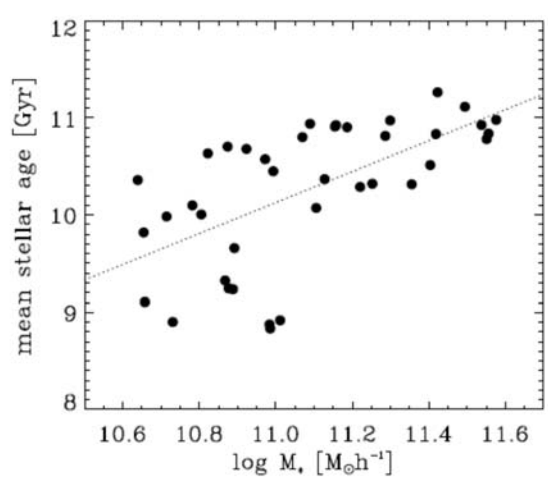
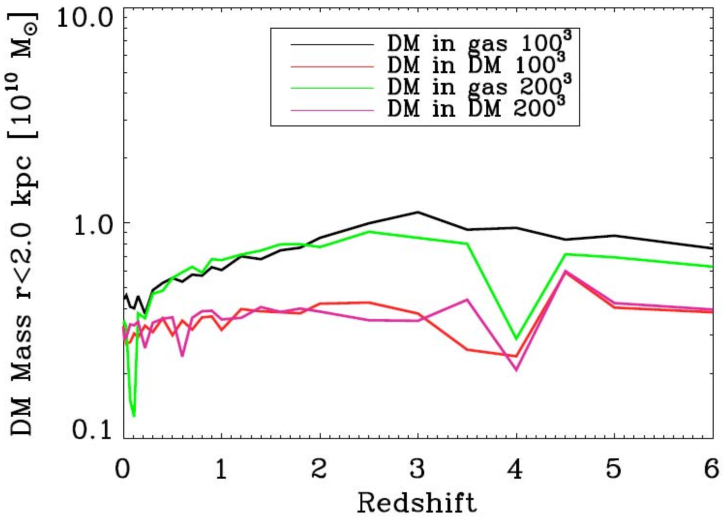


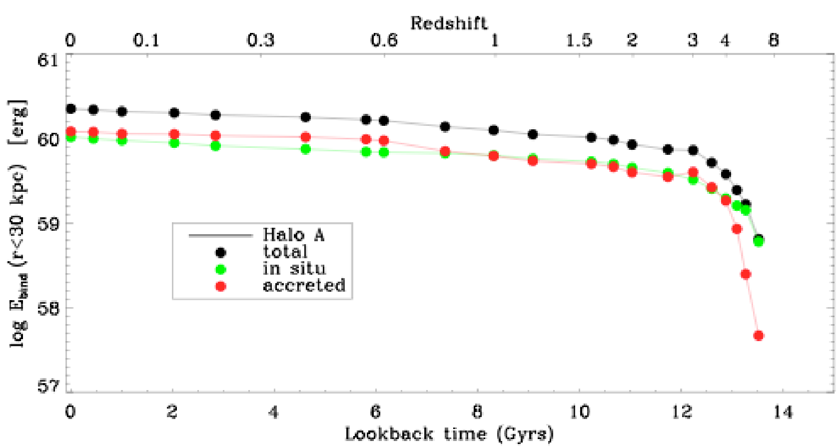
FIG. 12.— Mean age of the stars inside r_{10} as function of galaxy mass. High mass galaxies consist of older stars than the low mass galaxies, recovering the phenomenon usually referred to as 'archaeological downsizing' ($t_{mean} \propto \log M_*^{1.6}$).

Dark Matter Evolution - density declines in second phase



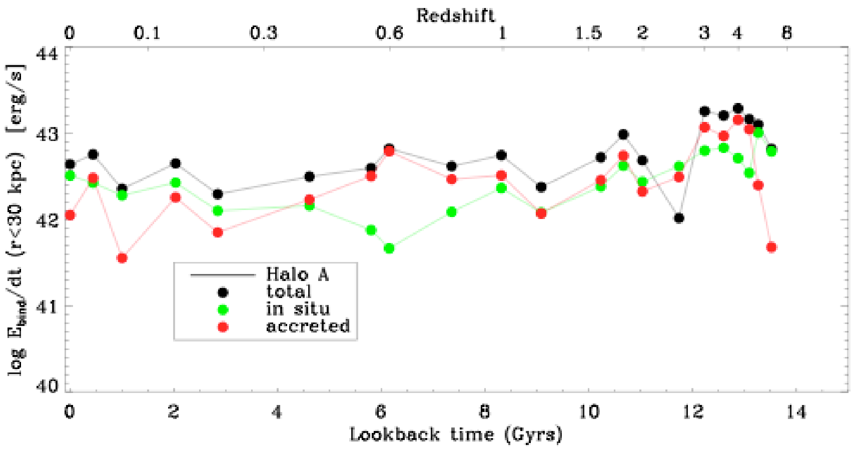
Binding Energy ~ 10^{60} erg from both in-situ and accreted stars:

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

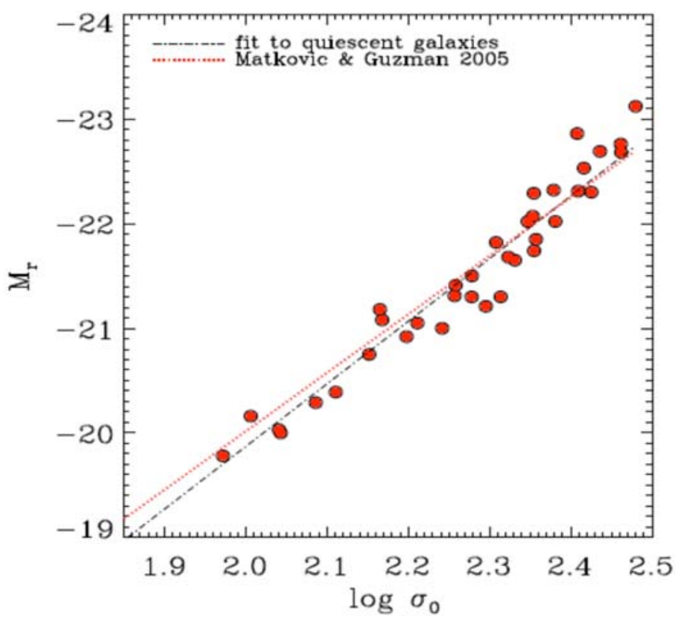


(B-E)/s~ $10^{42.5}$ erg/s from both in-situ and accreted stars:

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



Fit to observations is good



What have we learned? Old news.

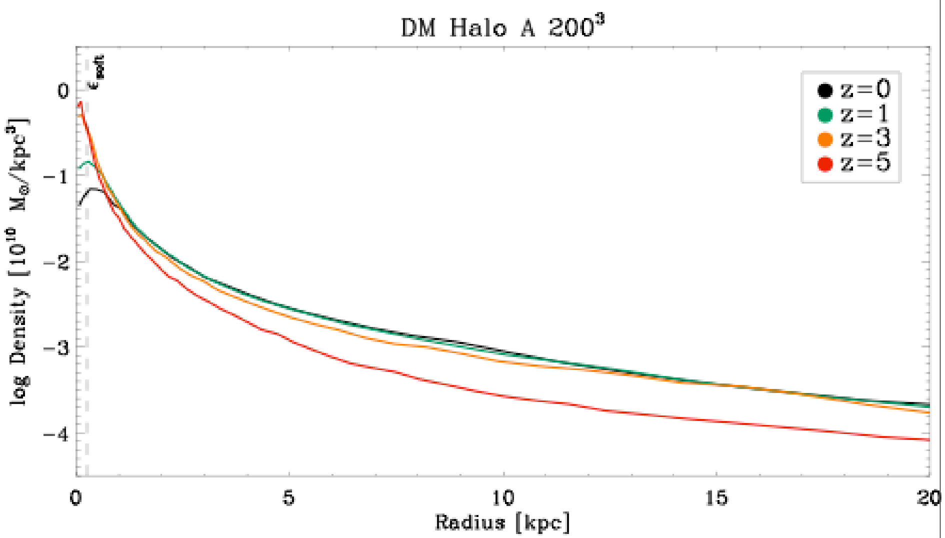
- For massive systems the 1977 work of Binney, Silk and Rees & Ostriker appears to be correct :

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.

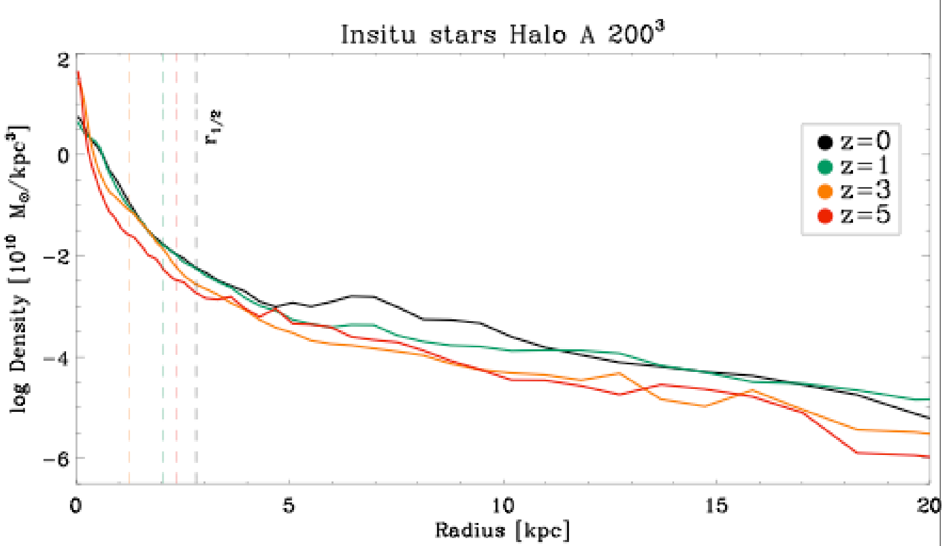
3) Why is there a dramatic evolution of size?
4) Why is galaxy "red and dead" early but continues to grow in luminosity?

- 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.

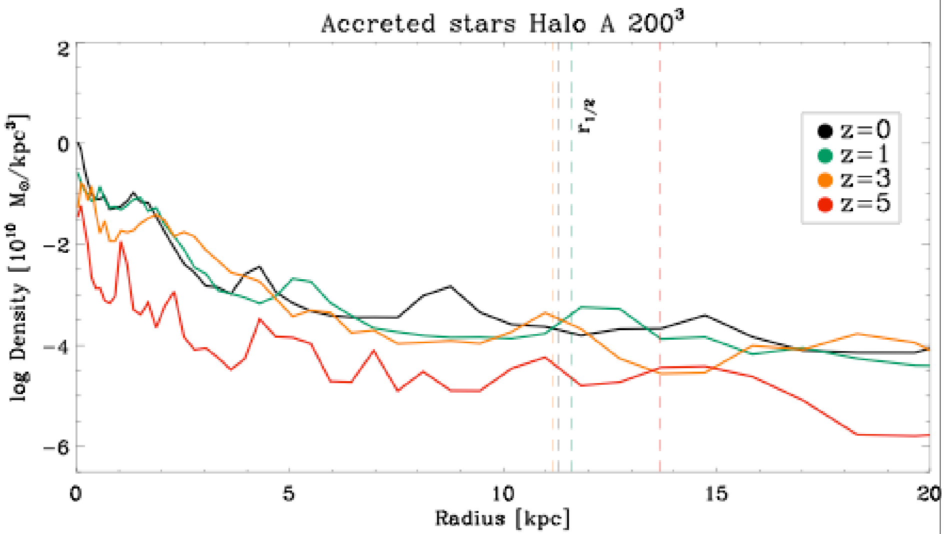
Details of Two Phase Growth



Details of Two Phase Growth -contd



Details of Two Phase Growth- contd



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:

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

If the "accretion" consists of "major mergers", with mass ratio unity, then ε is also unity and the above formulae reduce to the classic result,

BUT

If the added systems have much lower velocity dispersions than the original system, then $\varepsilon \ll 1$, and the velocity dispersion declines, with the surface density declining dramatically, as in the numerical simulations.

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.

To Be Done

- Do many more cases at high resolution; and repeat with different codes. ☑
- Look at X-ray properties._
- Improve gas cooling and radiative transfer._
- Repeat with SNI&II and AGN feedback._
- Add recycled gas._

(and make more mpgs!)